AFGROW European Workshop

Jun 23, 2022

ZHAW School of Engineering

Centre for Aviation

LexTech

AFGROW.NET

Agenda

Multisite Damage Solution

Solution for Combinations of Corner and Straight Through Cracks

New Weight Function Solutions

Part Through Cracked Hole Finite Width Effect Update

Recent Changes to the Residual Stress Capability

Spectrum Manager Software: Introduction and Demonstration

AFMAT Fracture Mechanics Database Demonstration

New Tabular Crack Growth Rate Lookup Database

Additional Parametric Crack Initiation Data

Implementing FAA Gust/Maneuver Exceedance Data in Spectrum Manager ?

New API 579 Pipeline Crack Solutions

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AFGROW Workshop 2020

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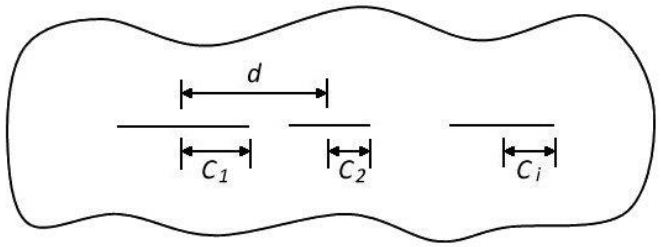
MSD Implementation in AFGROW

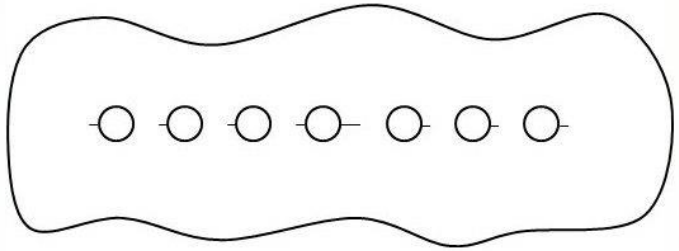
James Harter, Alexander Litvinov

LexTech, Inc .

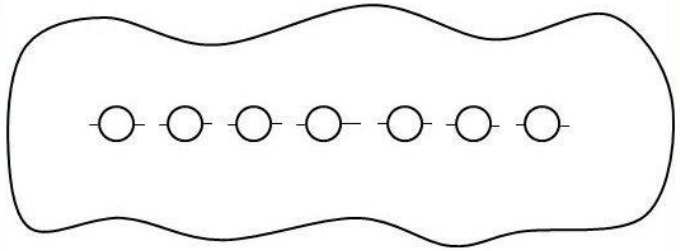
Through Crack Cases
(Infinite Plate)



Multiple Through Cracks

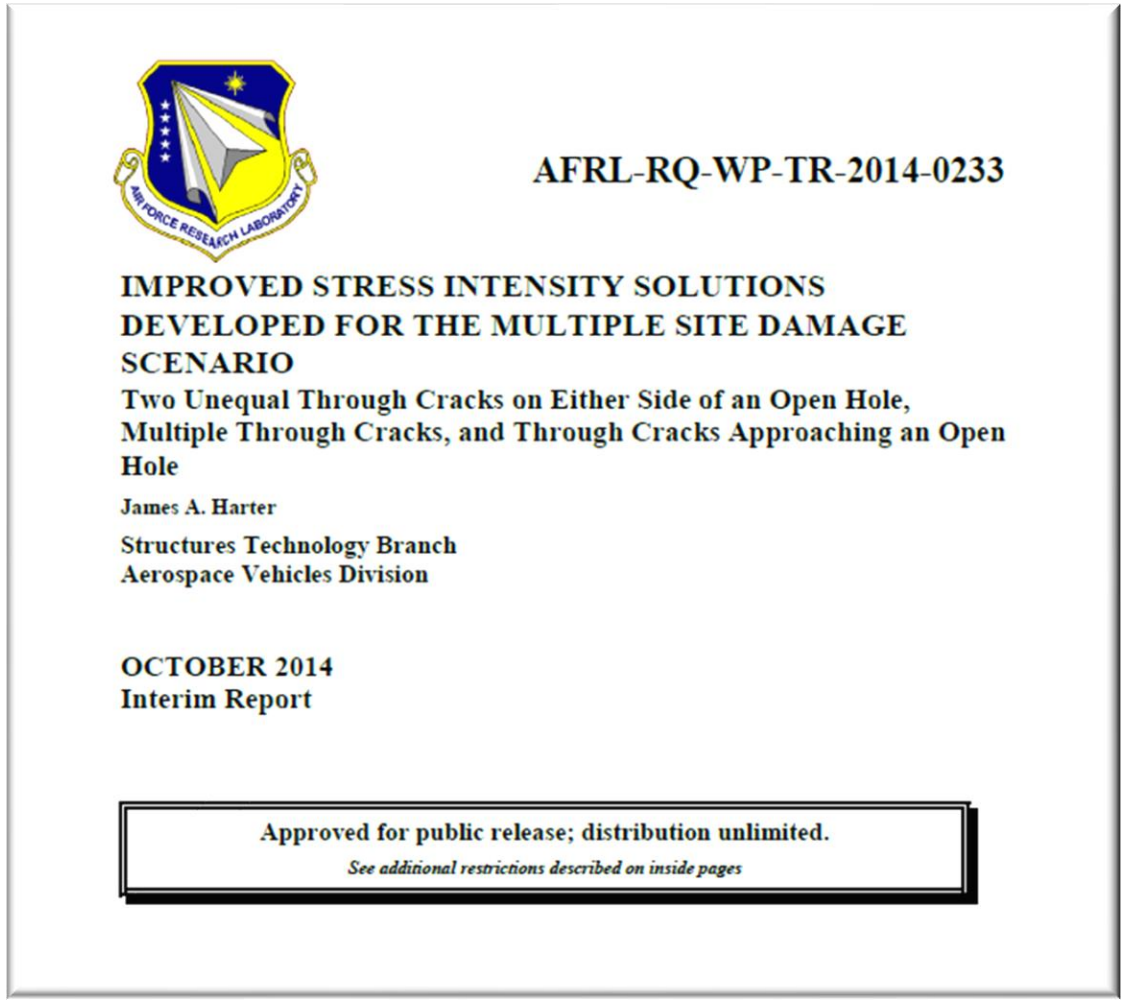


Multiple Holes, Continuing Damage



Multiple Holes, Full MSD Scenario

Baseline Reference



AFRL-RQ-WP-TR-2014-0233

IMPROVED STRESS INTENSITY SOLUTIONS DEVELOPED FOR THE MULTIPLE SITE DAMAGE SCENARIO

Two Unequal Through Cracks on Either Side of an Open Hole, Multiple Through Cracks, and Through Cracks Approaching an Open Hole

James A. Harter

Structures Technology Branch
Aerospace Vehicles Division

OCTOBER 2014
Interim Report

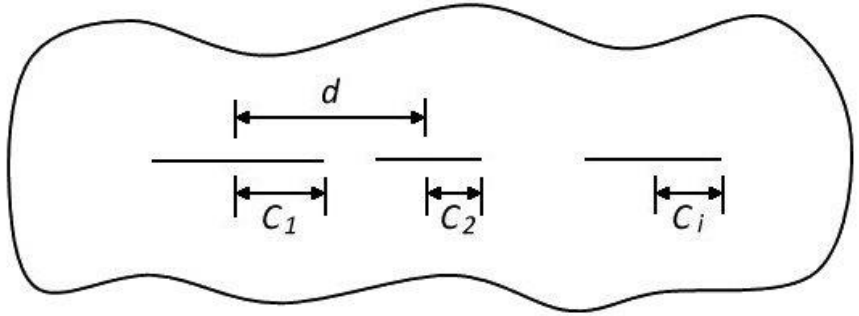
Approved for public release; distribution unlimited.

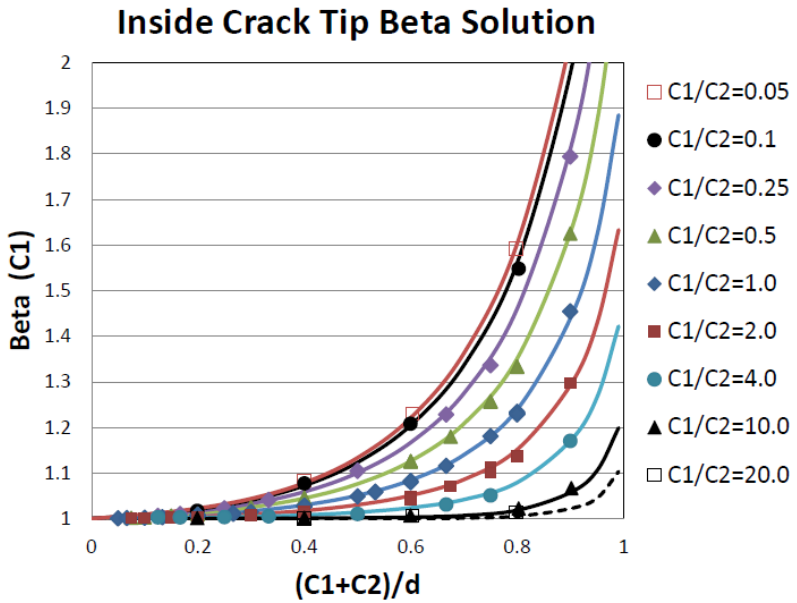
See additional restrictions described on inside pages

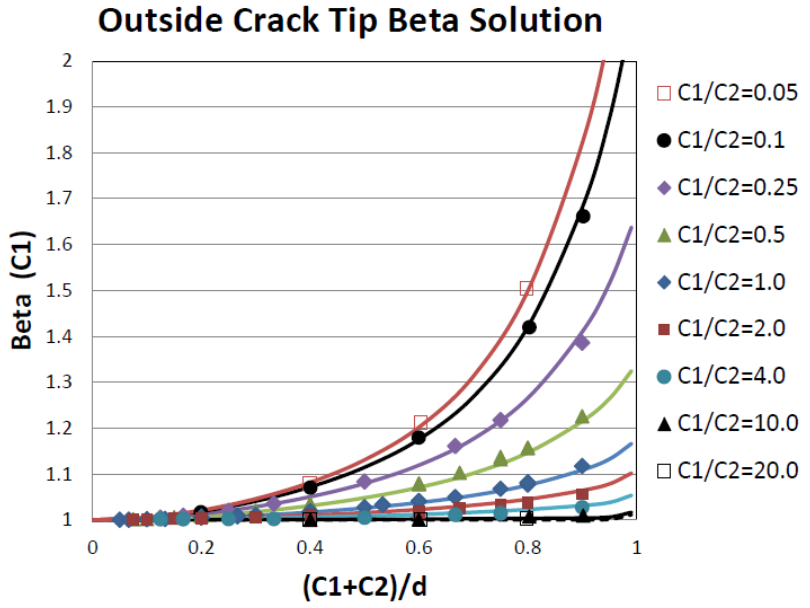
Multiple Through Crack Case

First, consider the two-crack case

Four crack tips (2 inside crack tips and 2 outside crack tips)
Two Parameters: C1/C2, and (C1 + C2)/d



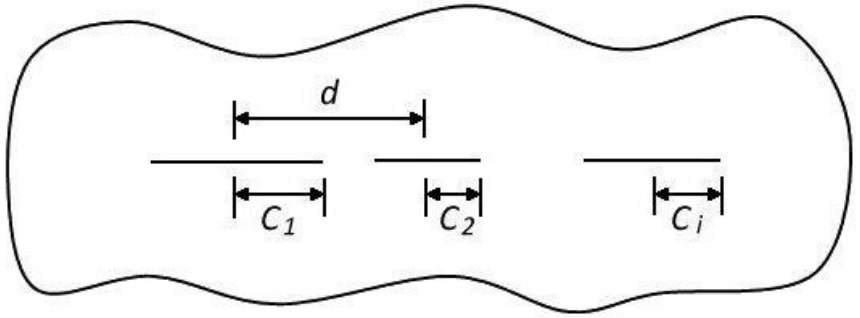




Curve fit solutions available in the baseline reference

Multiple Through Crack Case
Solution Procedure

- To solve for any number of through cracks, consider the crack of interest to be C_1 and calculate the beta value for each crack tip using the appropriate curve fit equation for each crack from 2 through i (total number of cracks).
- The inside crack tip is toward the adjacent crack and the outside crack tip is on the opposite side of the adjacent crack.
- AFGROW will allow 3 <= i <= 9 since the two crack solution is available in the Advanced Interface
- The method of compounding is used to calculate the final beta solution for each crack tip. $Beta_{total} = Beta_1 * Beta_2 * \ldots * Beta_{(i-1)}$



The curve fit solution is very good for each compounded case, but since the error is also compounded, it can increase somewhat as the number of cracks increase. However, this is mitigated since the distance between cracks also increases so that the solution for several compounded cases will eventually converge toward 1.0. Typical error will be < 3%

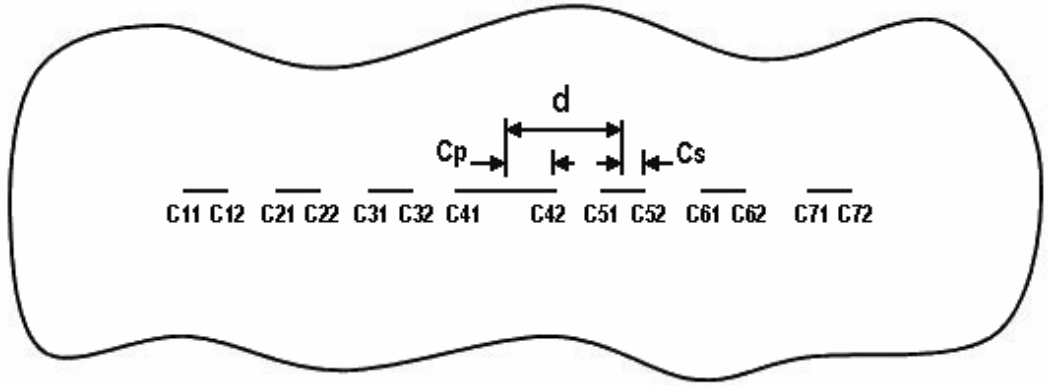
Multiple Through Crack Case
FEM Validation

Width	Spacing	Cp	Cs
75	0.5	0.1	0.05

	K	Beta	Eqn Beta	% Diff
C11	0.3991	1.006982	1.01012	0.3116
C12	0.3998	1.008748	1.02192	1.3057
C21	0.4027	1.016065	1.02043	0.4296
C22	0.4029	1.01657	1.02781	1.1057
C31	0.4074	1.027924	1.03343	0.5356
C32	0.4088	1.031457	1.03941	0.7711
C41	0.5687	1.014631	1.02394	0.9174
C42	0.5687	1.014631	1.02394	0.9174
C51	0.4088	1.031457	1.03941	0.7711
C52	0.4074	1.027924	1.03343	0.5356
C61	0.4029	1.01657	1.02781	1.1057
C62	0.4027	1.016065	1.02043	0.4296
C71	0.3998	1.008748	1.02192	1.3057
C72	0.3991	1.006982	1.01012	0.3116

Width	Spacing	Cp	Cs
150	1	0.1	0.05

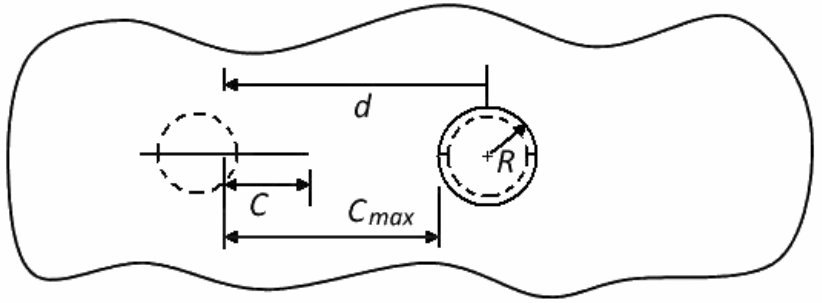
K	Beta	Eqn Beta	% Diff
0.3963	0.999917	1.00336	0.3443
0.3965	1.000422	1.00993	0.9504
0.3978	1.003702	1.00735	0.3634
0.3978	1.003702	1.01167	0.7938
0.399	1.00673	1.01148	0.4718
0.3991	1.006982	1.01448	0.7446
0.5623	1.003213	1.00841	0.5180
0.5623	1.003213	1.00841	0.5180
0.3991	1.006982	1.01448	0.7446
0.399	1.00673	1.01148	0.4718
0.3978	1.003702	1.01167	0.7938
0.3978	1.003702	1.00735	0.3634
0.3965	1.000422	1.00993	0.9504
0.3963	0.999917	1.0036	0.3683



FEM width set as 150 * d to approximate an infinite plate

Multiple Cracked Holes
Axial Load Case

We use the current AFGROW Advanced Model solution for two unequal through cracks at a hole and apply corrections for cracked, adjacent holes using the method of compounding.

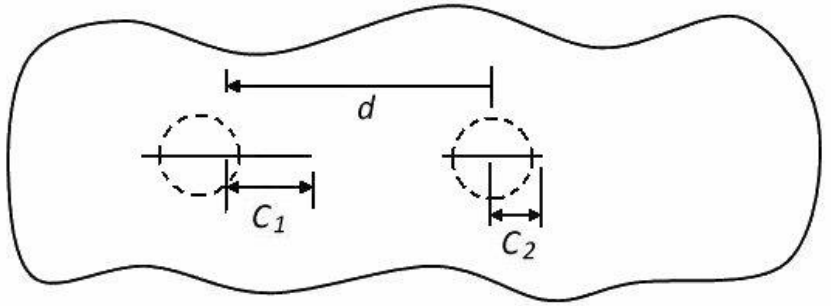


Crack Approaching a Hole

Two Possible Corrections

If the crack(s) at an adjacent hole are small (<= R/3), then we use the correction from the baseline reference for a through crack approaching a hole.

If the crack(s) at an adjacent hole are larger (> R/3) , we use the correction for a crack approaching another crack. This correction was explained in previous slides.



Crack Approaching a Crack

Through Crack Approaching a Hole
Correction

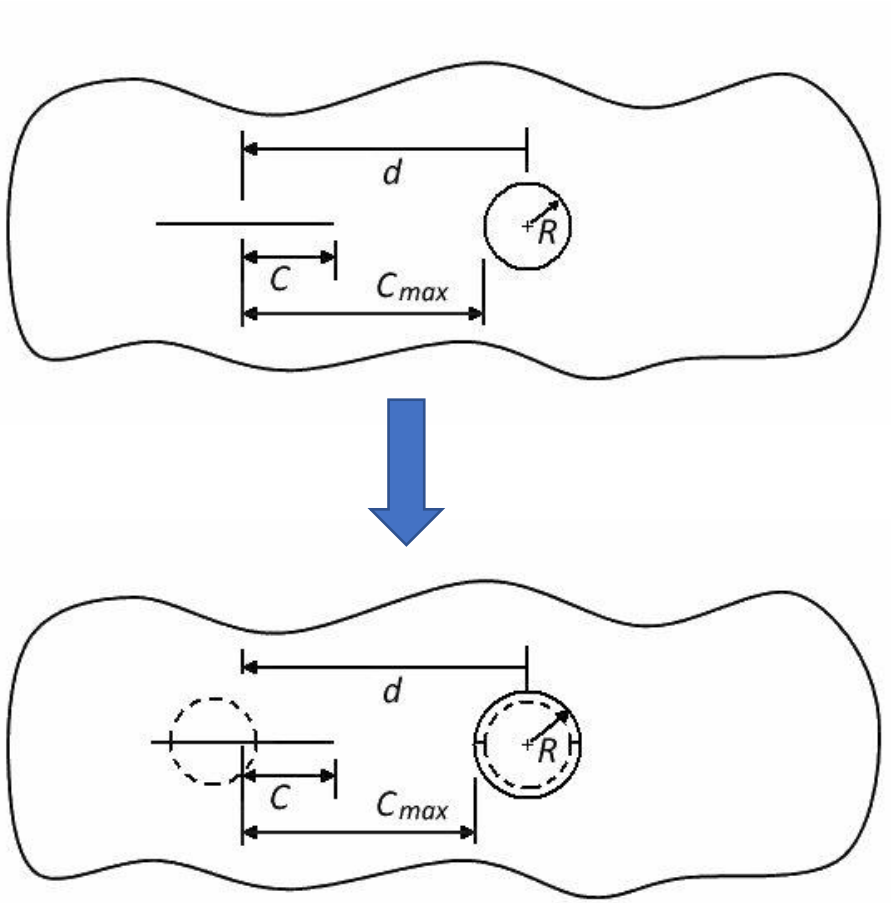
The hole of interest is assumed to be a through crack extending across the hole where the total length includes the crack(s) and the hole diameter. The new crack length and center is calculated.

The radius and center of the adjacent cracked hole is modified as required to create a new hole radius that extends to the edge of the crack(s).

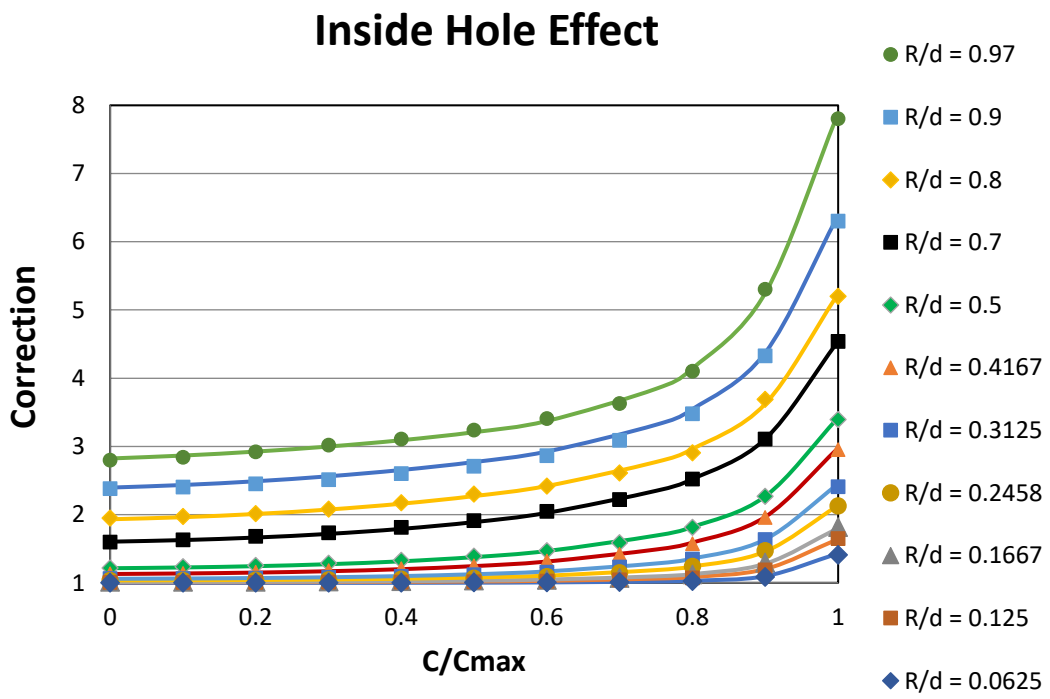
Two possible crack tips

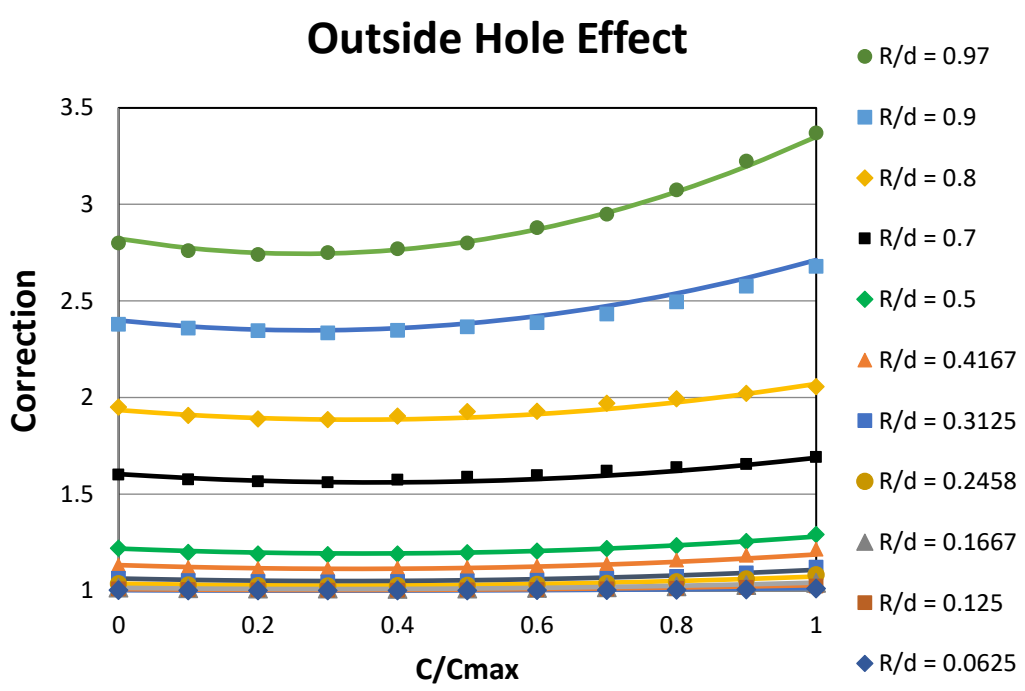
1 inside crack tip (toward the hole) and 1 outside crack tip (away from the hole)

Two Parameters: R/d, and C/C_{max}



Through Crack Approaching a Hole Correction

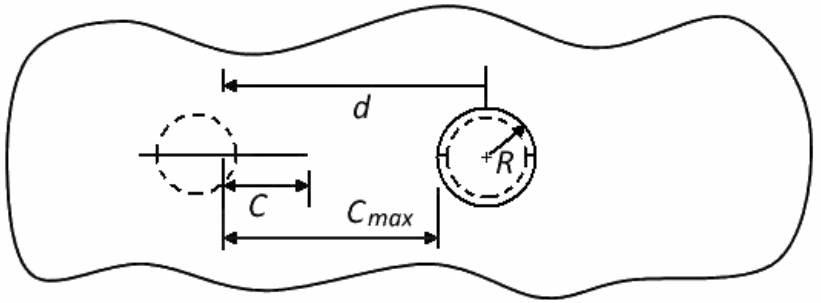




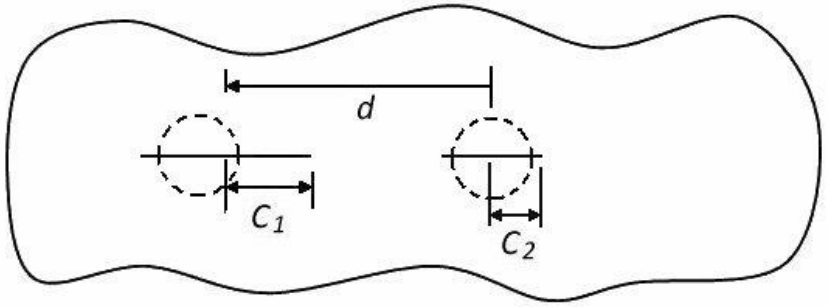
Curve fit solutions available in the baseline reference

Multiple Cracked Holes
Solution Procedure

- To solve for any number of holes, start from the hole of interest, calculate the beta solution for a given crack tip using the Advanced Model Solution for one or two non-symmetric cracks with no adjacent holes. Calculate the beta correction value for each adjacent cracked hole using the appropriate correction model for each hole from 3 through i (total number of holes).
- The inside crack tip is toward the adjacent hole and the outside crack tip is on the opposite side of the adjacent hole.
- AFGROW will allow 3 <= i <= 9 (odd number)
- The method of compounding is used to calculate the final beta correction for each crack tip. $Correction_{total} = Correction_1 * Correction_2 * \ldots * Correction_{(i-1)}$



Crack Approaching a Hole



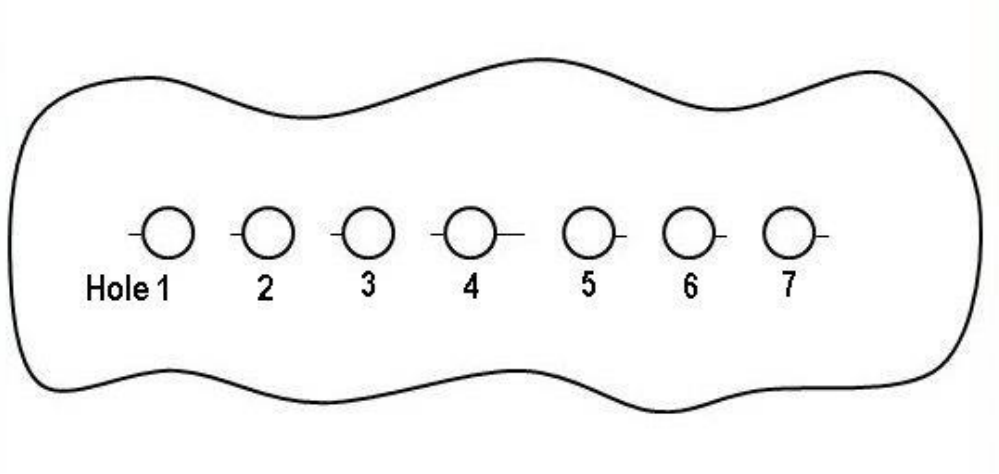
Crack Approaching a Crack

Multiple Cracked Holes
FEM Validation

Hole Dia.	Spacing	Pin Load	ByPass	Thickness	Width	Height
0.25	4D	0	10	0.04	50	250

Cp	Cs
0.05	0.005

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
K	3.165	3.201	3.213	3.291	7.228	3.215	3.201	3.165
	Beta							
Beta	2.525	2.554	2.564	2.626	1.824	2.565	2.554	2.525
Equation	2.494	2.517	2.521	2.624	1.784	2.521	2.516	2.494
Diff (%)	-1.231	-1.466	-1.645	-0.084	-2.202	-1.715	-1.474	-1.234



Cp	Cs
0.25	0.1

	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
K	8.080	8.270	8.401	10.380	10.410	8.495	8.284	8.084
	Beta							
Beta	1.442	1.475	1.499	1.852	1.175	1.516	1.478	1.442
Equation	1.406	1.440	1.466	1.849	1.183	1.480	1.442	1.407
Diff (%)	-2.471	-2.376	-2.221	-0.154	0.670	-2.380	-2.413	-2.479

Bearing Load Effect on Adjacent Holes

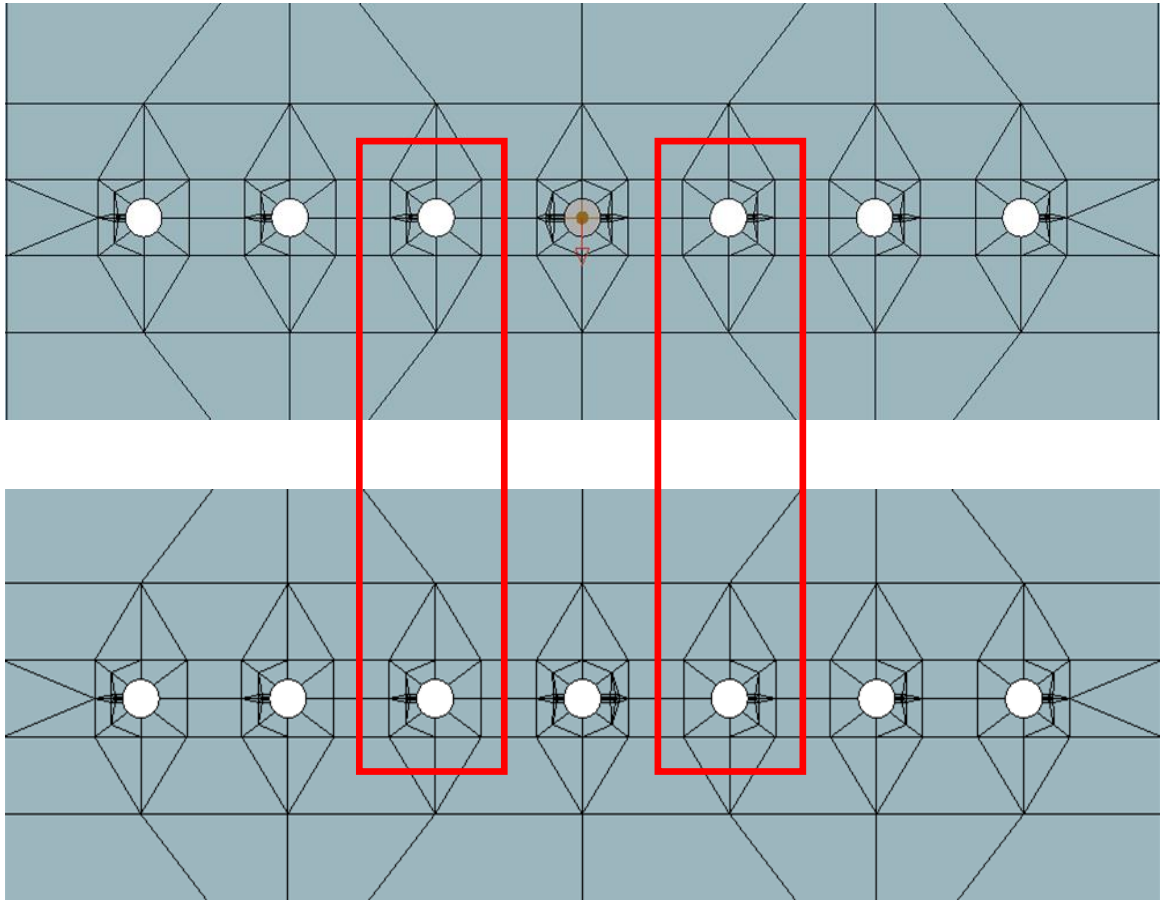
Width (in)	Total Height (in)	Thickness (in)	Hole Dia (in)	Spacing (hole dia)	ByPass (Ksi)	Pin Load (Kip)	Fastener Material
50	250	0.04	0.25	4	10	0.2	Steel

Pin Load in Center Hole Only			
Cp	Cs	Kp	Ks
0.1	0.05	10.96	11.16

Adjacent Holes	
K Left	K Right
7.819	7.832

No Bearing Load (all open holes)			
Cp	Cs	Kp	Ks
0.1	0.05	8.562	8.46

Adjacent Holes	
K Left	K Right
7.652	7.661



New Bearing Load Solution for Multiple Holes

We have developed a bearing solution for the multiple hole geometry that accounts for the following effects:

- Different bearing loads at each hole
- Influence of bearing load on adjacent holes

This solution is currently being validated and we plan to include it in our upcoming new release.

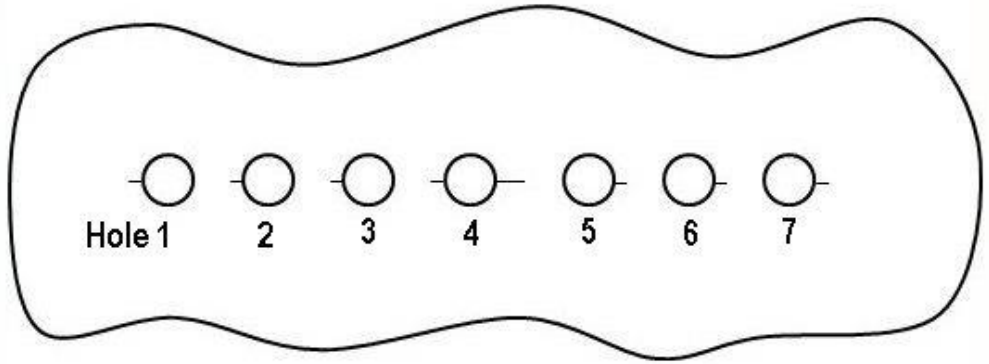
Multiple Cracked Holes
FEM Validation

Hole Dia.	Spacing	Pin Load	ByPass	Thickness	Width	Height
0.25	4D	0.4	10	0.04	50	250

	Cp	Cs						
	0.05	0.005						
	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
K	8.433	8.418	8.341	8.602	13.87	8.358	8.422	8.435
Equation	7.758	7.855	7.901	8.246	14.412	7.908	7.856	7.758
Diff (%)	-8.003	-6.684	-5.275	-4.143	3.909	-5.390	-6.718	-8.022

	Cp	Cs						
	0.075	0.025						
	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
K	12.830	12.980	12.980	13.930	14.360	13.000	12.990	12.830
Equation	12.842	13.028	13.121	14.312	14.725	13.137	13.030	12.843
Diff (%)	0.096	0.367	1.089	2.745	2.540	1.050	0.306	0.101

	Cp	Cs						
	0.1	0.05						
	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
K	13.710	14.000	14.070	15.570	14.880	14.090	14.000	13.710
Equation	14.183	14.425	14.552	16.161	15.228	14.573	14.428	14.184
Diff (%)	3.453	3.036	3.426	3.794	2.339	3.429	3.057	3.460

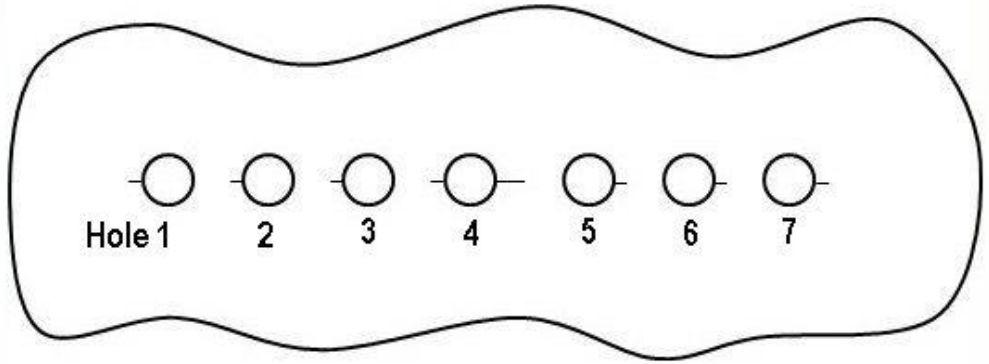


	Cp	Cs						
	0.25	0.1						
	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
K	13.850	14.360	14.600	18.240	16.030	14.750	14.380	13.860
Equation	14.451	14.806	15.064	18.711	16.511	15.208	14.825	14.457
Diff (%)	4.341	3.103	3.177	2.580	2.999	3.103	3.094	4.309

Multiple Cracked Holes
FEM Validation

		Hole 4	Other Holes				
Hole Dia.	Spacing	Pin Load	Pin Load	ByPass	Thickness	Width	Height
0.25	3D	0.5	0.25	10	0.04	50	250

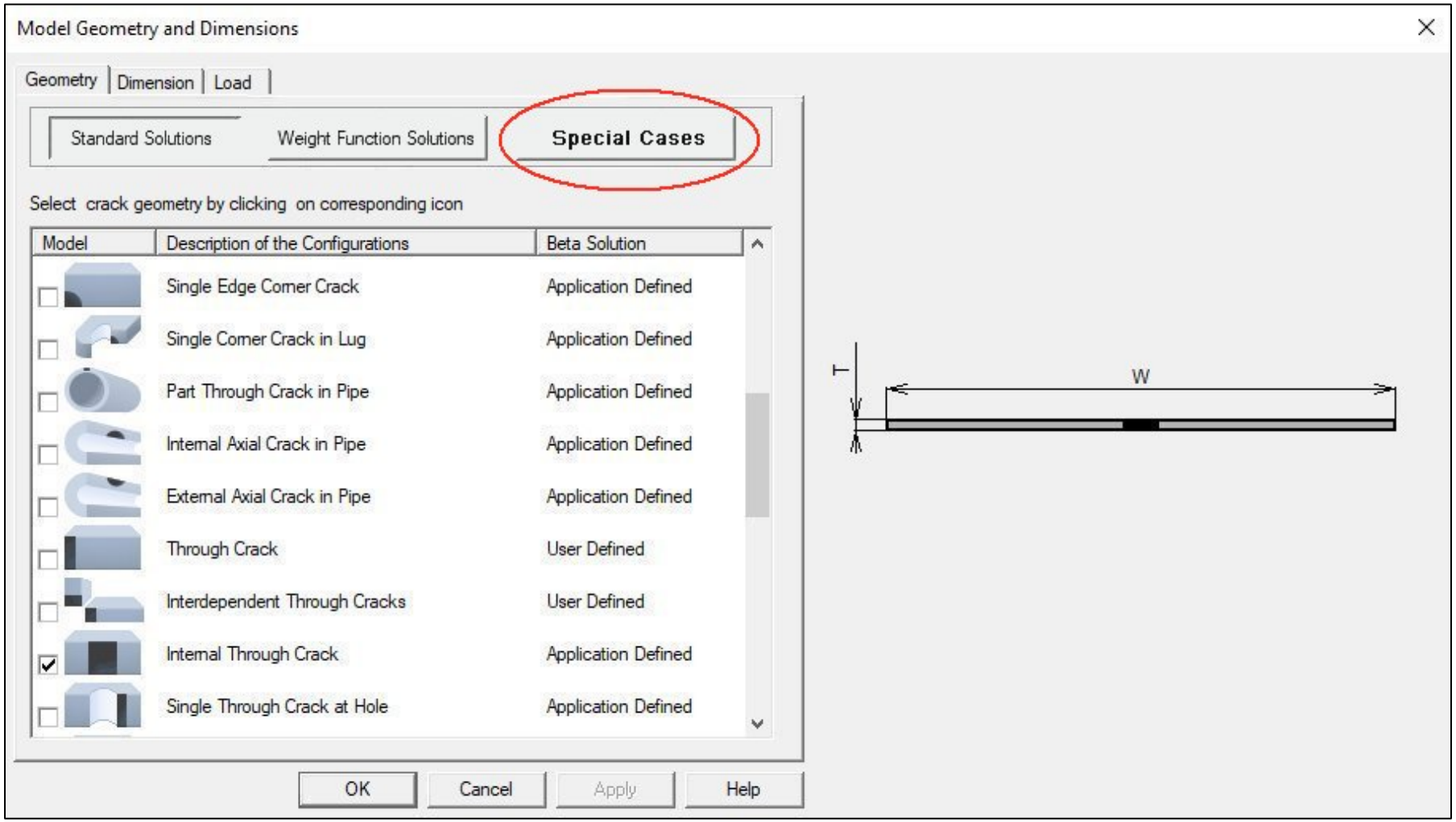
	Cp	Cs						
	0.1	0.05						
	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
K	11.690	12.230	12.530	17.560	16.670	12.590	12.240	11.700
Equation	11.872	12.223	12.915	17.884	16.638	12.977	12.228	11.874
Diff (%)	1.559	-0.057	3.070	1.844	-0.195	3.076	-0.097	1.483



		Hole 4	Other Holes				
Hole Dia.	Spacing	Pin Load	Pin Load	ByPass	Thickness	Width	Height
0.25	6D	0.5	0.25	10	0.04	50	250

	Cp	Cs						
	0.1	0.05						
	Stress Intensity							
	Hole 1	Hole 2	Hole 3	Hole 4		Hole 5	Hole 6	Hole 7
K	10.950	11.030	11.110	16.250	15.230	11.120	11.030	10.950
Equation	11.165	11.230	11.513	16.636	15.369	11.517	11.231	11.165
Diff (%)	1.965	1.815	3.624	2.376	0.911	3.574	1.820	1.966

Implementation



Proposed Special Cases

Multiple Through Cracks in an Infinite Plate

- Axial load case
- 3 to 7 cracks

A secondary crack is added on each side of the model to simulate an infinite plate condition for all cracks in the model

Multiple Through Cracked Holes in an Infinite Plate (Continuing Damage)

- Axial and bearing load cases
- Primary and Secondary Crack at the Center Hole
- Single Secondary Crack on Outside of each adjacent hole (2, 4, or 6 holes)

A secondary cracked hole is added on each side of the model to simulate an infinite plate condition for all cracks in the model

LexTech

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Questions/Comments?

Combinations of Corner and Straight Through Cracks at a Hole

Alexander Litvinov and Jimmy Lambert

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LexTech

AFGROW.NET

New Weight Function Solutions

Alexander Litvinov

LexTech, Inc .

Finite Width Correction for Part-Through Cracked Holes

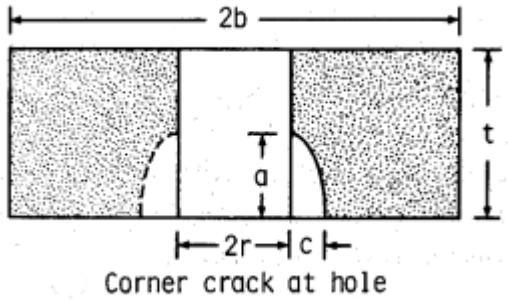
James Harter, Senior Consultant for LexTech, Inc .

Finite Width Correction

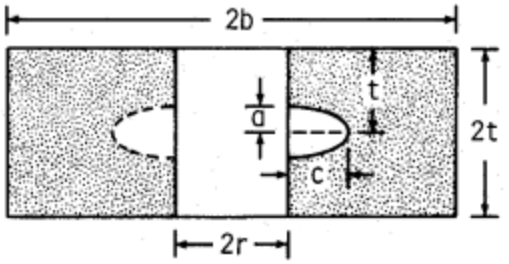
Current Closed-Form Finite Width Correction

$$F_w = \left[\sec\left(\frac{\pi\, r}{2\, b}\right)\sec\left(\frac{\pi(2r+nc)}{4(b-c)+2nc}\sqrt{\frac{a}{t}}\right)\right]^{1/2} \quad *$$

n = 1 for a single crack
n = 2 for two, symmetric cracks
W = $2b$
D = $2r$



Corner crack at hole



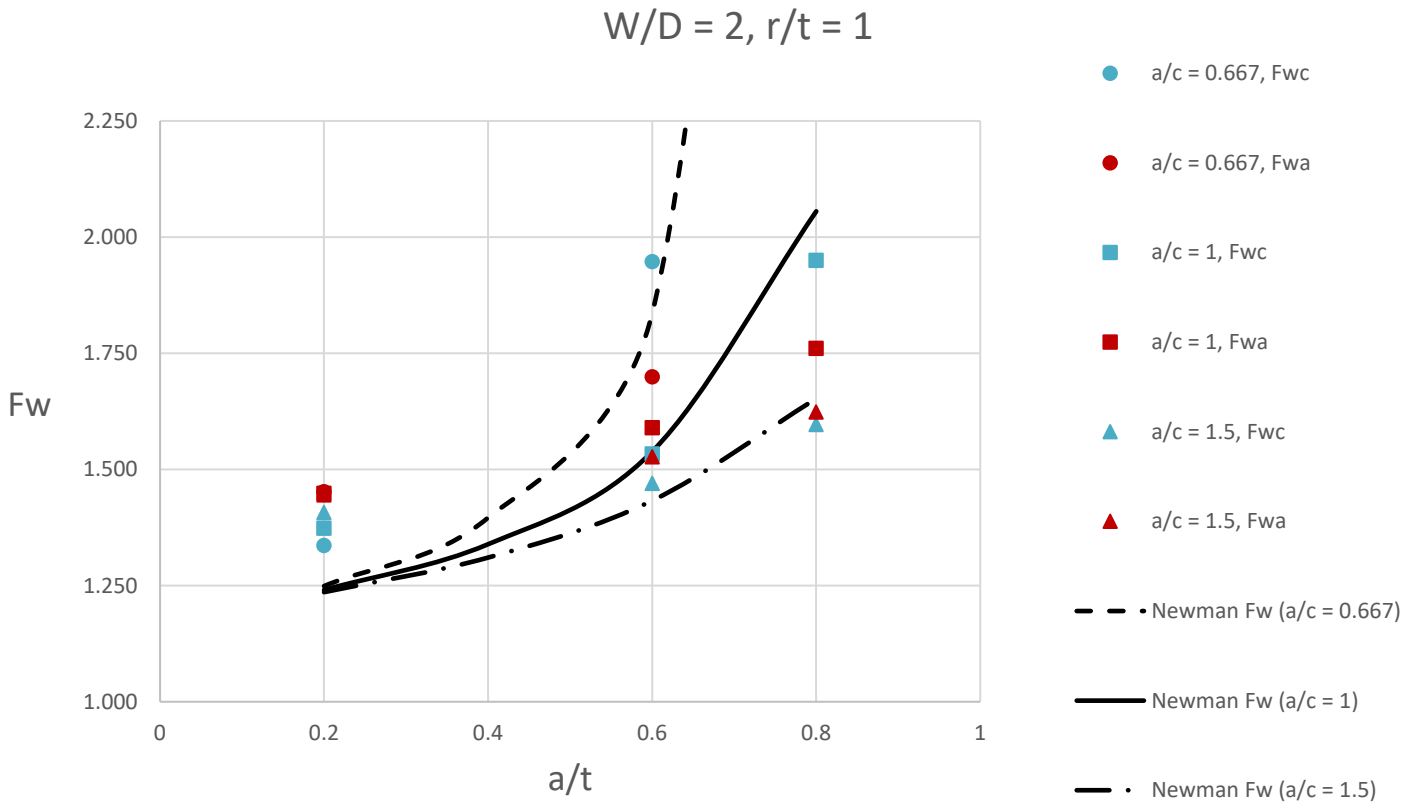
Surface crack at hole

This correction is applied to all points on a given crack front
for a given a and c dimension as indicated in reference documentation

* Newman, J.C., and Raju, I.S., "Stress Intensity Factor Equations for Cracks in Three-Dimensional Bodies Subjected to Tension and Bending Loads," Chapter 9, Computational Methods in the Mechanics of Fracture, Elsvier Science Publishers B.V., 1986, Equation 62.

Finite Element Model Results *

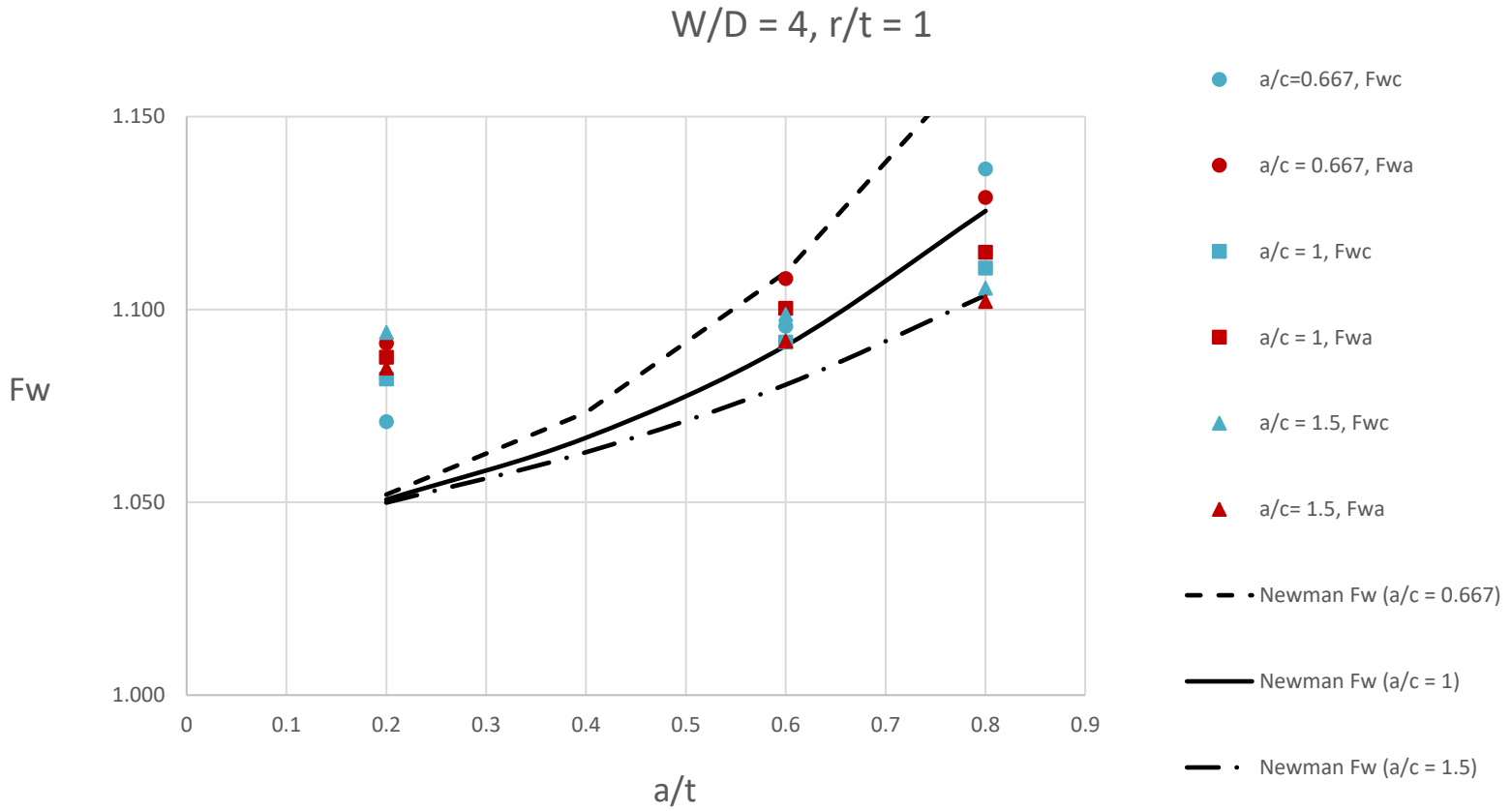
Single Corner Cracked Hole



* SimModeler (Dr. Adrian Loghin)

Finite Element Model Results *

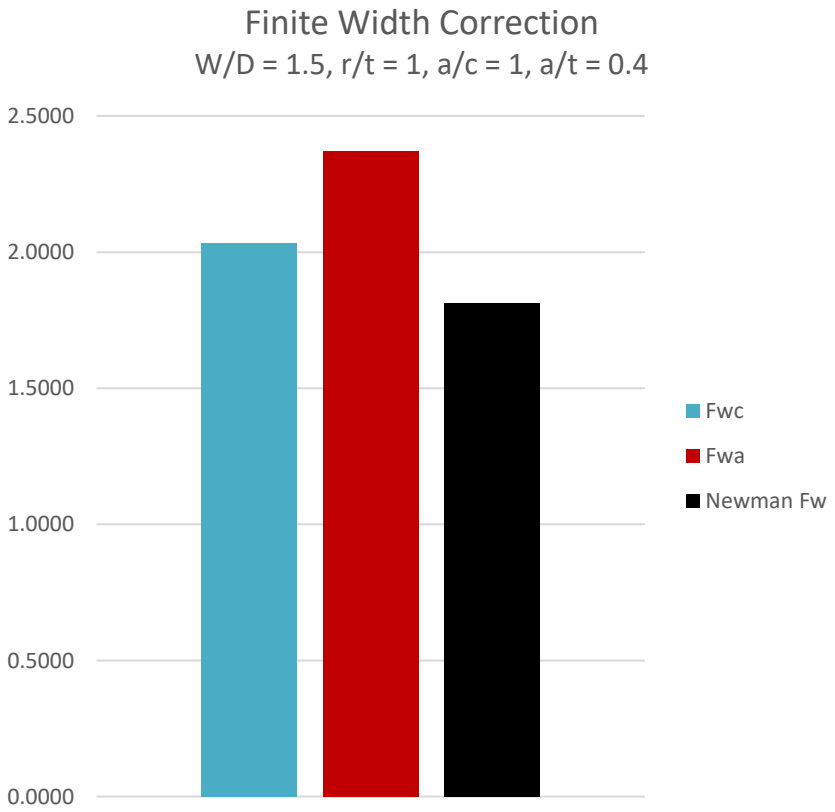
Single Corner Cracked Hole

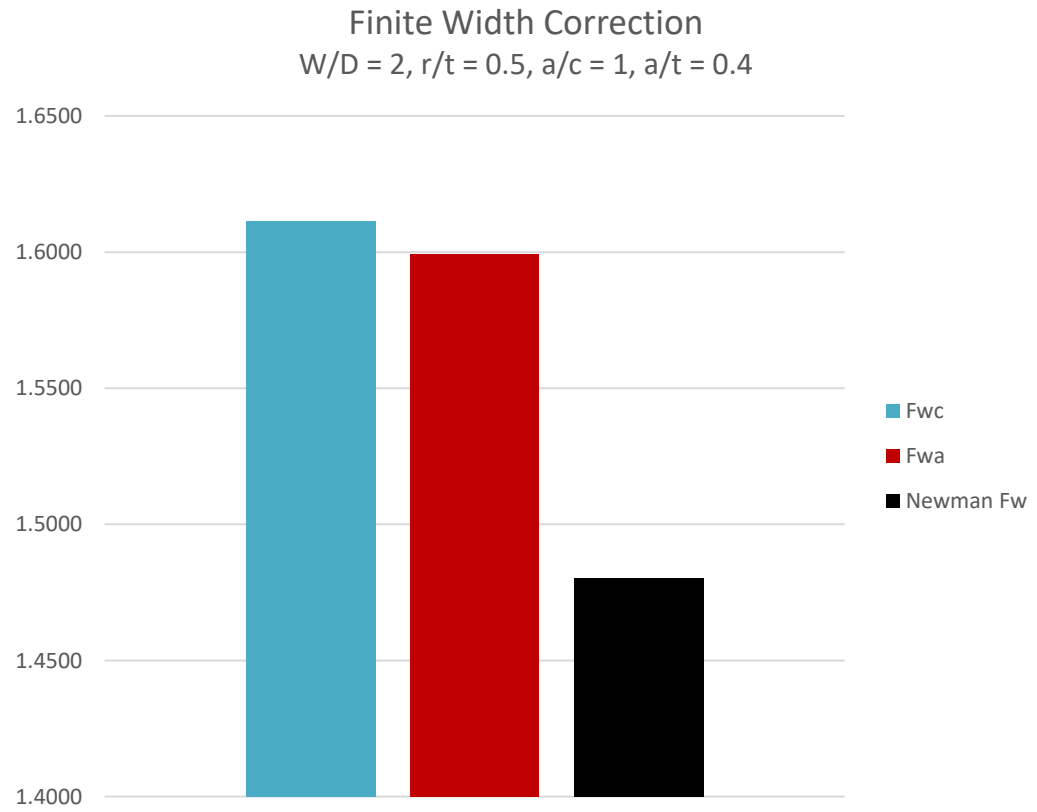


* SimModeler (Dr. Adrian Loghin)

Finite Element Model Results *

Single Corner Cracked Hole

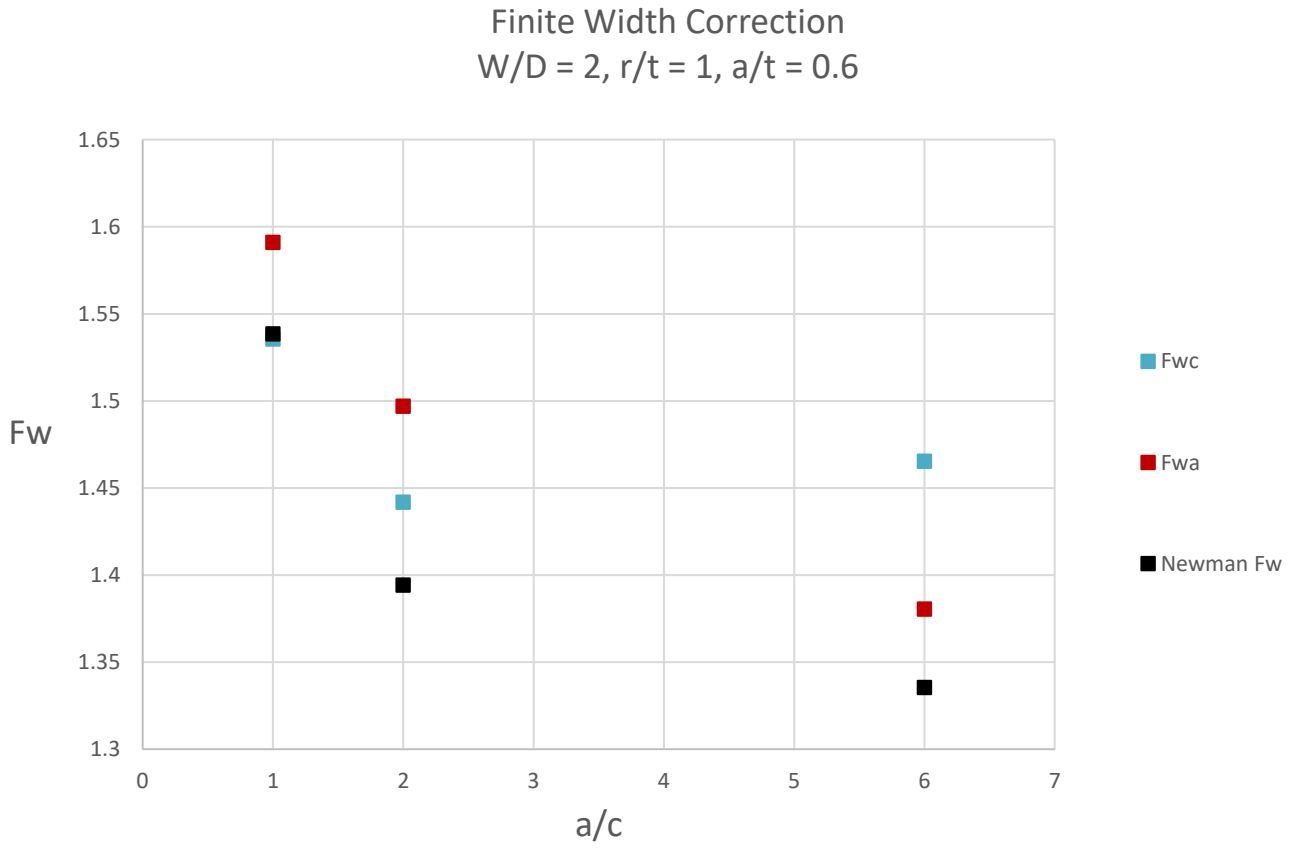




* SimModeler (Dr. Adrian Loghin)

Finite Element Model Results *

Effect of Crack Aspect Ratio



* SimModeler (Dr. Adrian Loghin)

What Do We Know?

The 1986 Newman Fw correction is low when a/t < 0.6

The 1986 Newman Fw correction tends to be high when a/t > 0.6

The actual Fw is not the same for each crack dimension

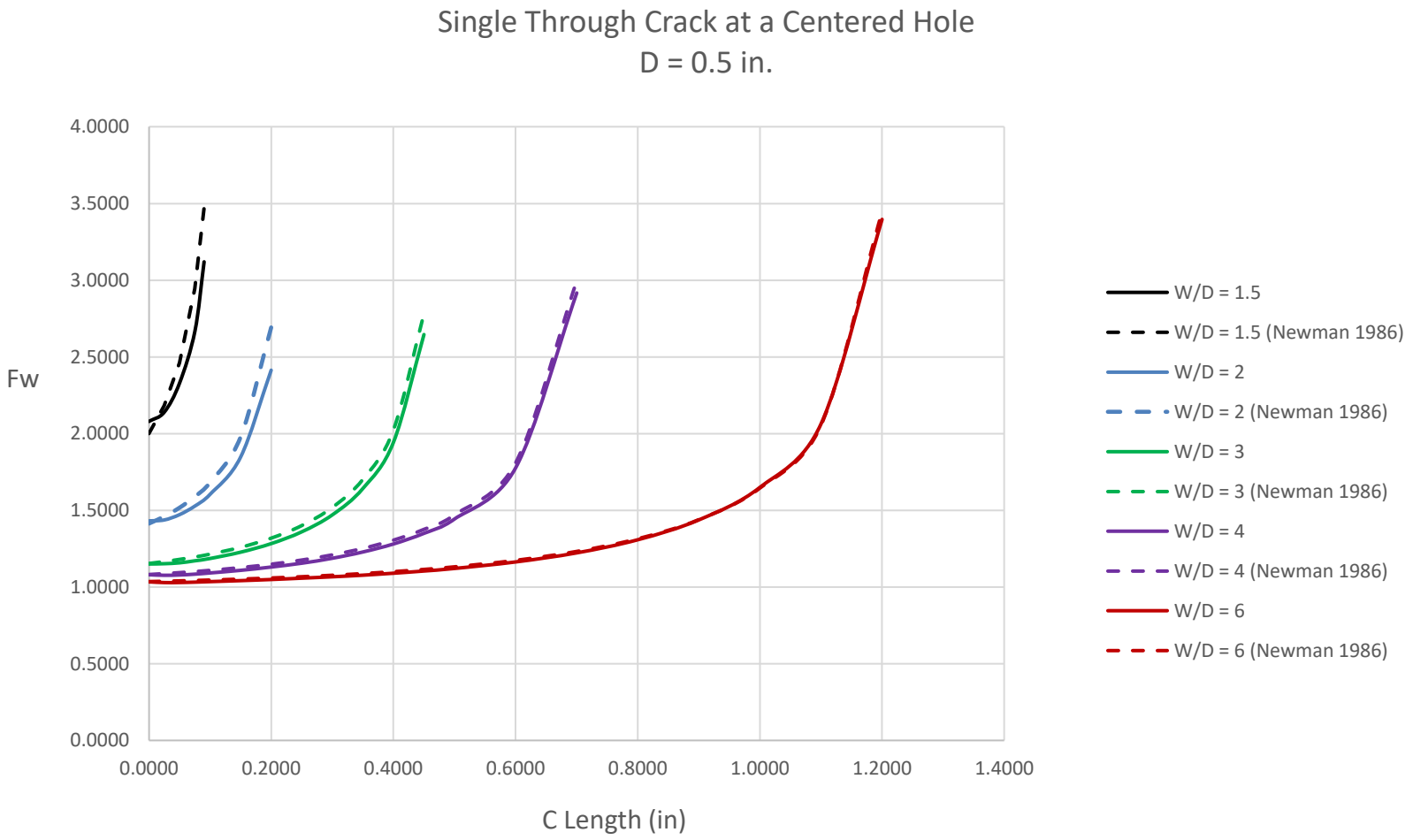
Fw appears to be a function of W/D, r/t, a/c, and a/t

We have a problem when using the Newman correction for corner cracked holes

What is the Plan Moving Forward?

- Review/Modify the Current AFGROW Finite Width Solution for the Through Crack (2-D) Case - Completed
- Develop an Initial FEM Solution Matrix for a Single Corner Cracked Hole – Completed
- Obtain FE Solutions for the Initial Matrix – Completed by Dr. Scott Prost-Domasky (APES, Inc.)
- Develop a New Closed-Form Finite Width Correction for the Corner Cracked Hole Geometry – Completed
- Verify and Validate the Solution – Completed
- Apply to Double Corner Cracks and Surface Cracks – Plan to include as an optional preference
- Implement in AFGROW – In progress
- Determine How to Apply the Solution Along the Crack Front – Not Started

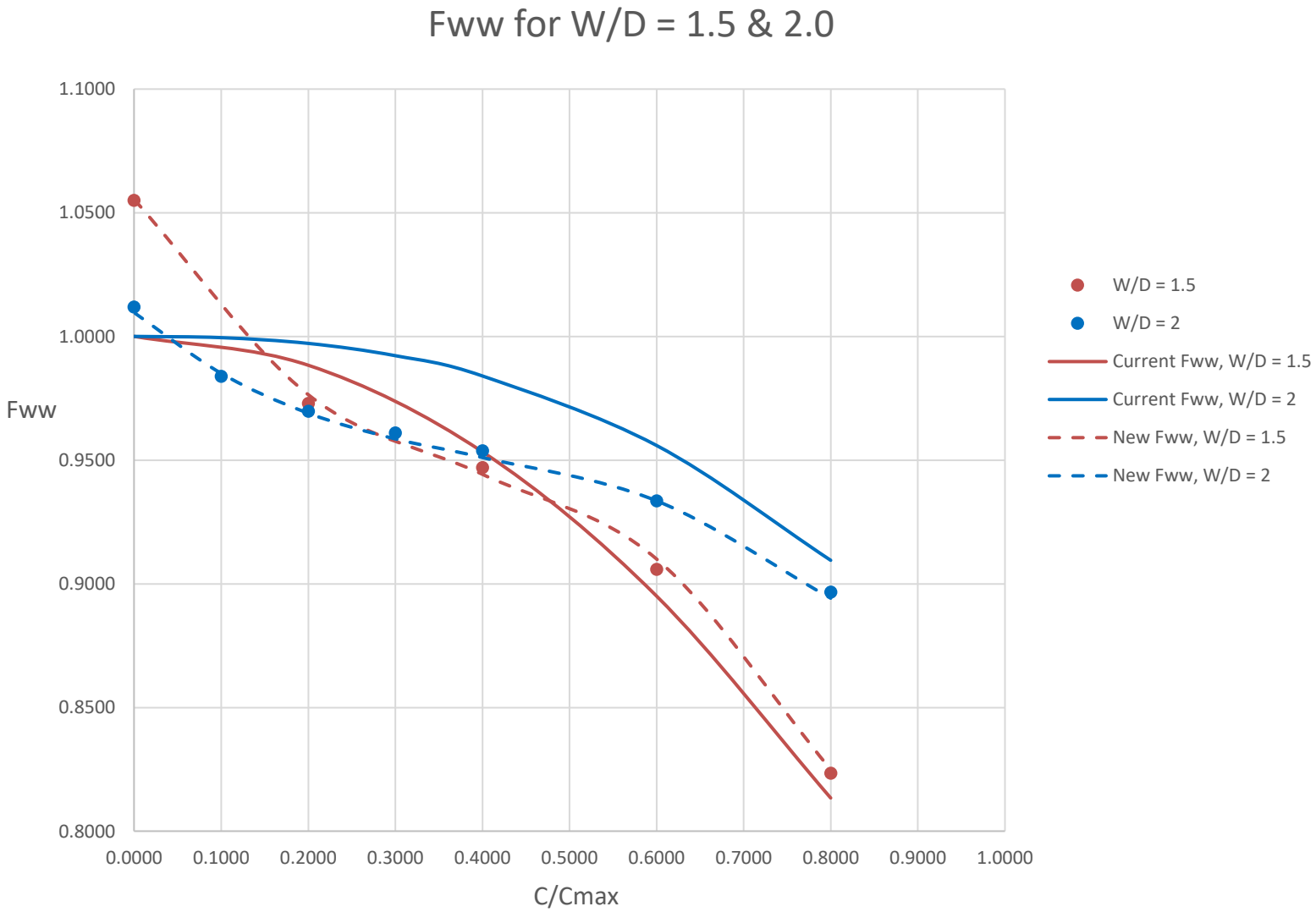
Through Cracked Hole Finite Width Correction



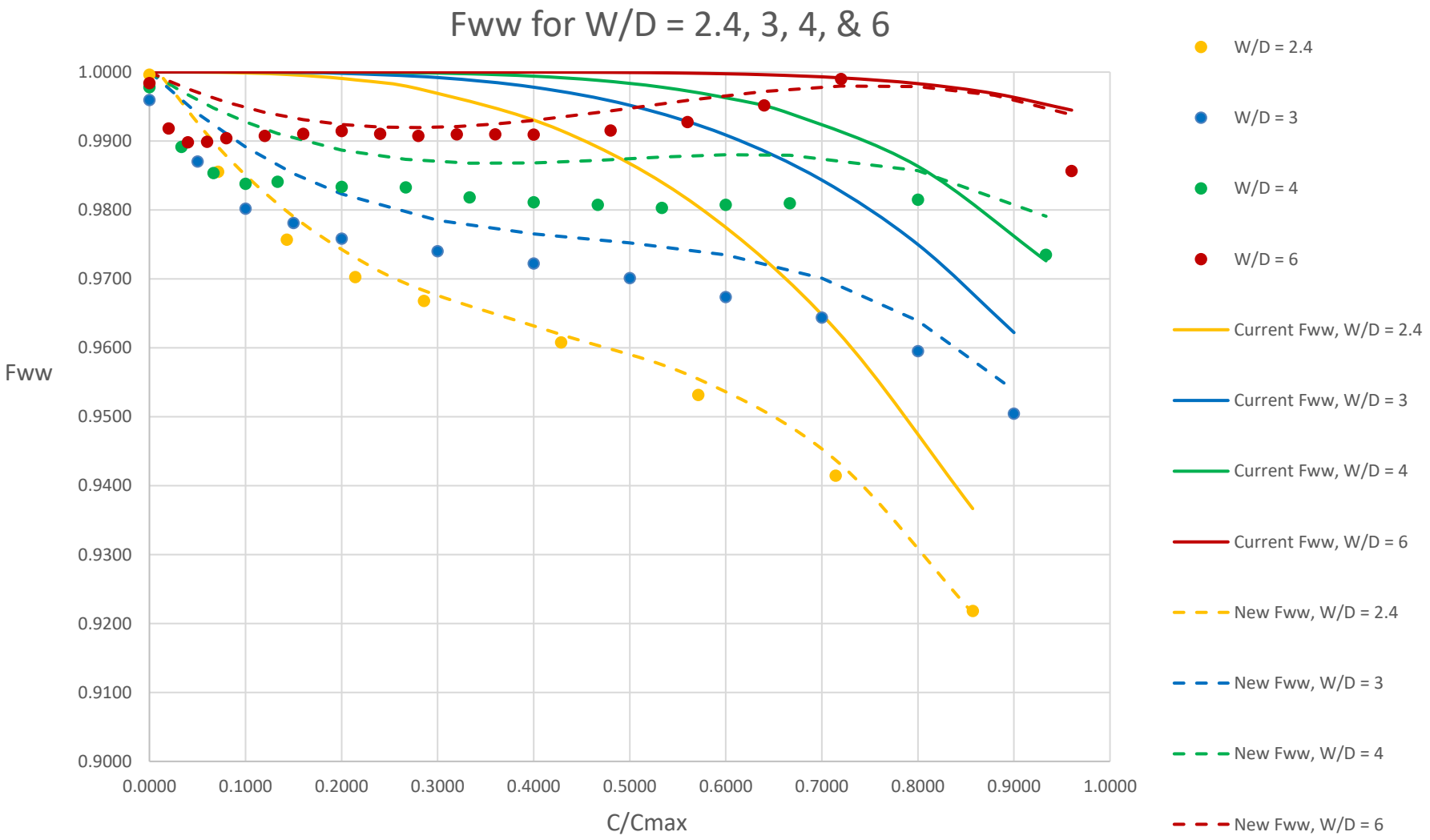
Through Cracked Hole Finite Width Correction

- The through crack finite width correction is used as the baseline solution for all 3-D finite width corrections
- The 3-D width correction must converge to the 2-D correction as (a/t, a, & c) → 0 (both directions) and a/t → 1 (c-direction only)
- The Width Correction for a=c=0 is the unflawed Kt value for any W/D divided by 3
- AFGROW currently uses the 1986 Newman/Raju width correction (F_w) with a/t = 1 and a modification (F_{ww}) to correct it for W/D <= 6
- This has recently been reviewed, and a new correction has been developed
- We would like the correction to apply for W/D >= 1.5

Through Cracked Hole Finite Width Modification



Through Cracked Hole Finite Width Modification



Through Cracked Open Hole Finite Width Correction Summary

- The modified Fww correction for a single through crack at a hole is much better than the current correction for (W/D <= 2) and is within << 1% of FE solutions
- The new Fww correction is also better than the current correction for (2 < W/D < 6) and is conservative within 1% of FE models
- For W/D > 6, Fww > 0.99, converges to 1.0 as W/D → 50 and is within <<1% of the required width correction
- The applicability of the new Fww correction still needs to be validated for the double, symmetric through crack case

Part-Through Finite Width Correction

- The through crack finite width correction ($F_w * F_{ww}$) is used as the baseline solution for all 3-D finite width corrections
- The part-through crack correction is defined for any point (x) as $\left(\frac{K}{K_\infty}\right) / (F_w F_{ww}) = F_x$ *
- Dr. Scott Prost-Domasky provided the StressCheck© results for the initial 3-D solution matrix for a single corner cracked hole
- Wide plate K_∞ values for the a and c-dimensions were obtained from the Fawaz-Andersson single corner cracked hole solutions in AFGROW
- Required parameter coverage for compatibility with the Fawaz-Andersson solution database are (0.1 < r/t < 10), (0.1 < a/c < 10), (0 < a/t < 1)

* Where x refers to either the a or c crack growth direction

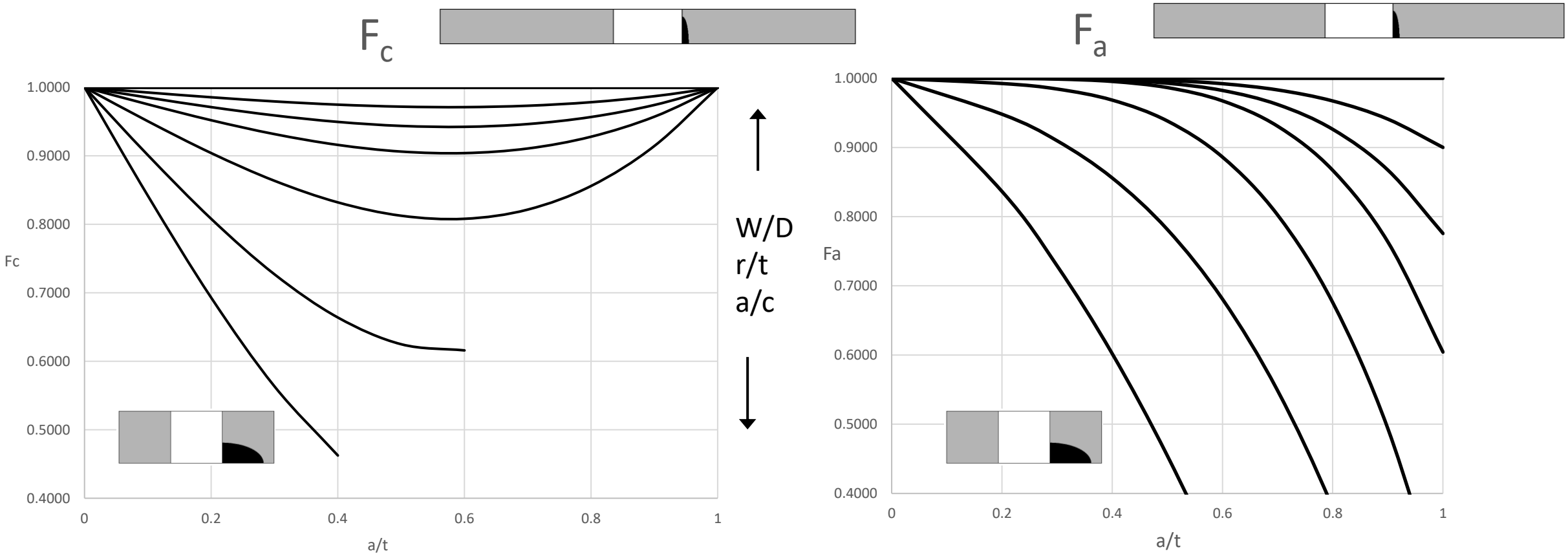
Initial Single Corner Cracked Hole Solution Matrix

Prost-Domasky (APES)

W/D	r/t	a/c	a/t
1.5	0.5	0.5	0.2
2.0	1.0	1.0	0.4
4.0	2.0	1.5	0.6
6.0	4.0	2.0	0.8
10.0		4.0	0.9
		6.0	

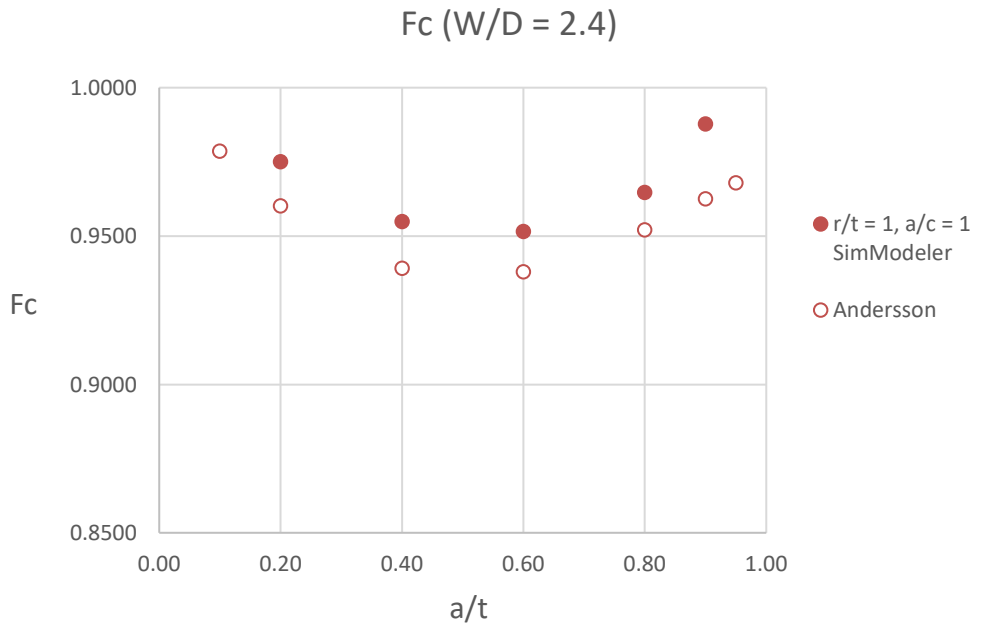
Note: The full matrix was not used for all W/D values, but was concentrated between W/D = 2 and 4. A smaller subset of the matrix was used for W/D = 1.5, 6, and 10. Also, some combinations of these parameters are not physically possible.

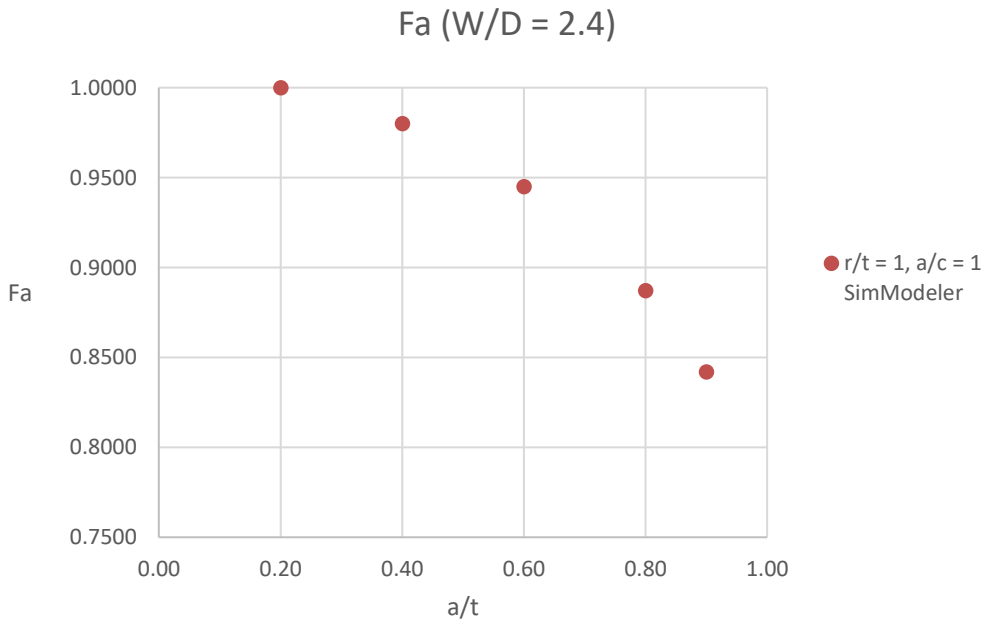
Part-Through Finite Width Correction Trends



Part-Through Finite Width Correction Examples

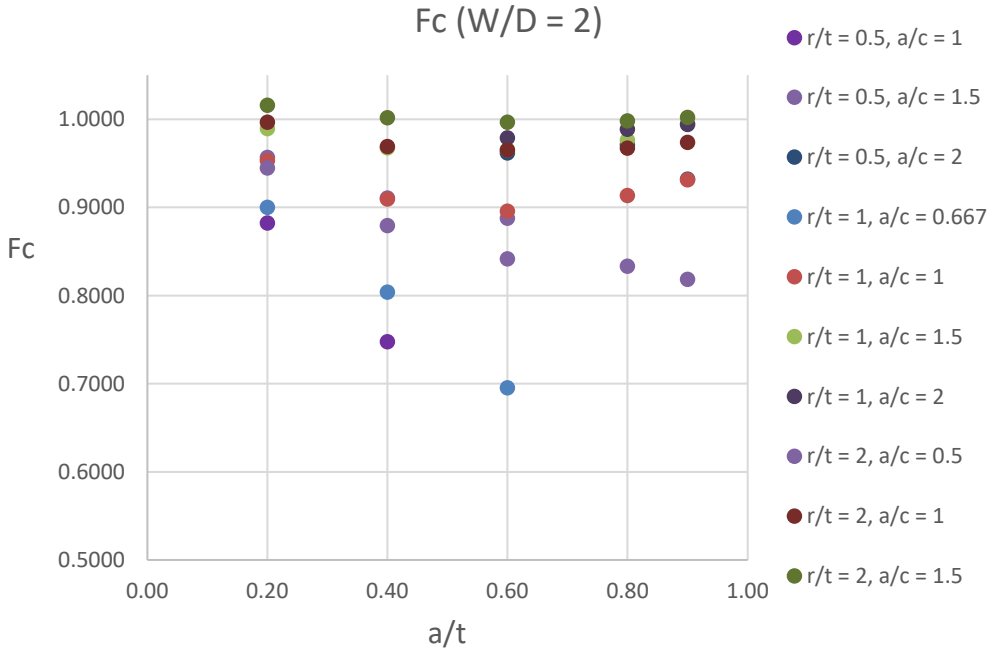
ERSI RR Narrow Plate Case

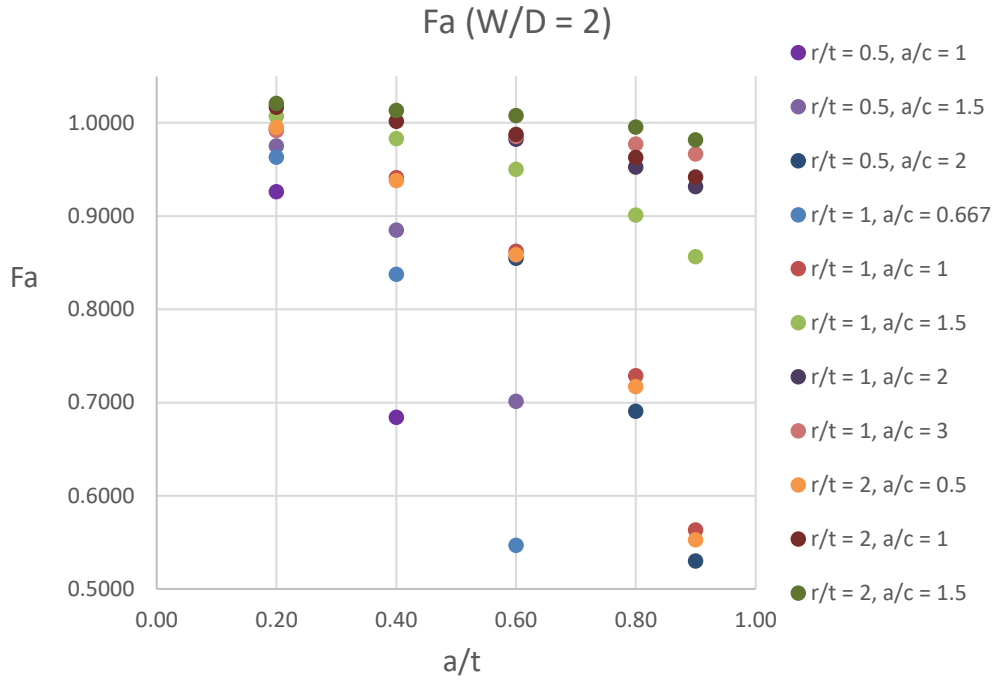




Part-Through Finite Width Correction Examples

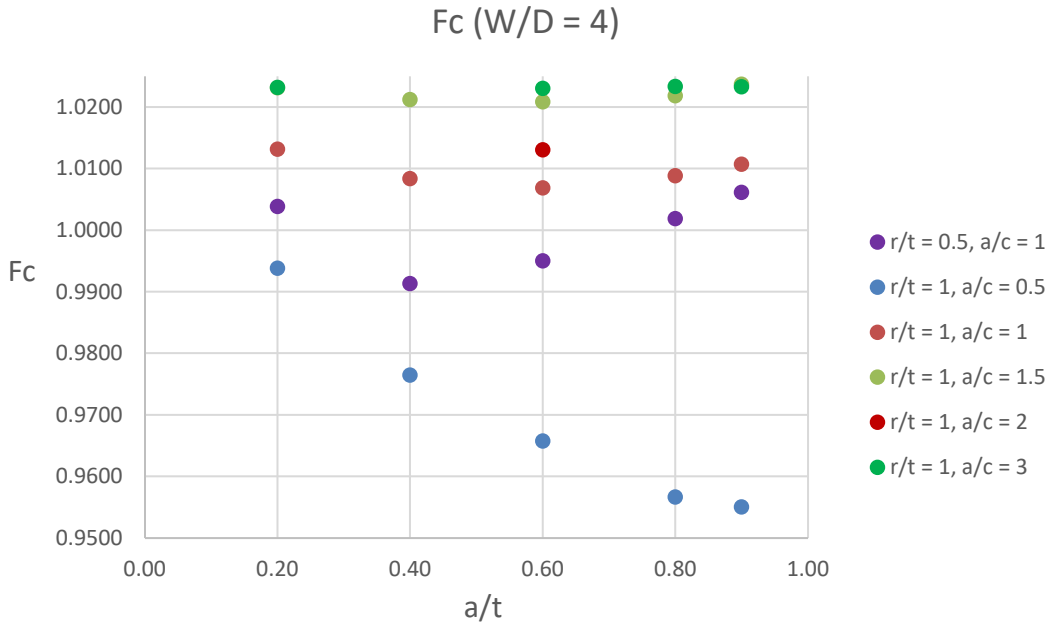
Prost-Domasky (APES) Solutions

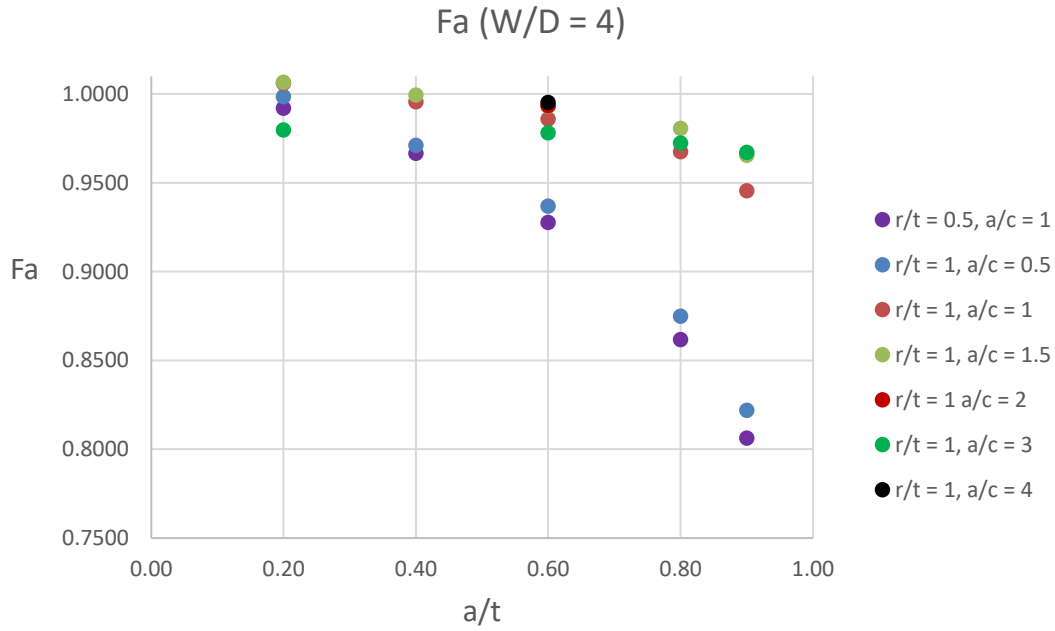




Part-Through Finite Width Correction Examples

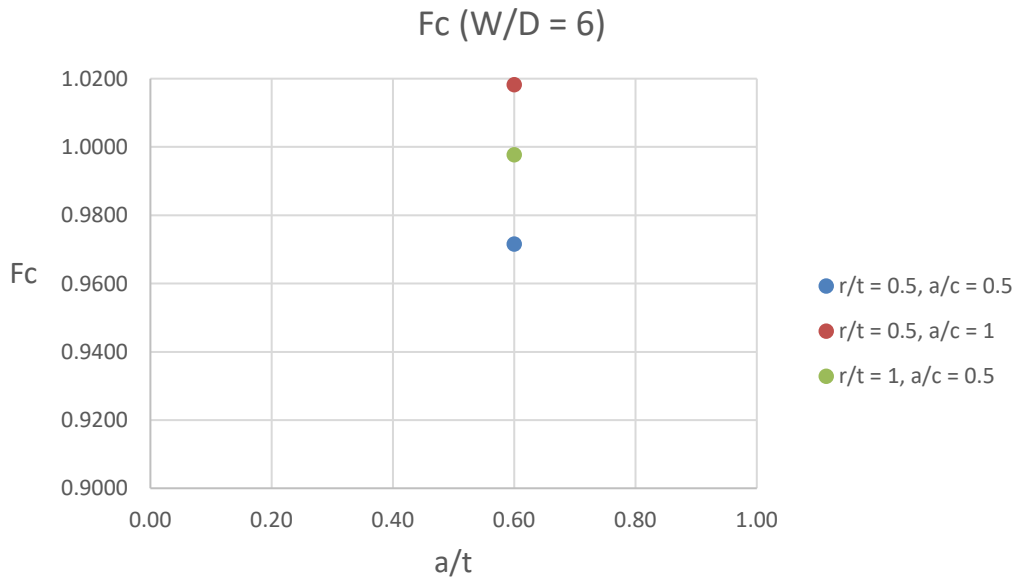
Prost-Domasky (APES) Solutions

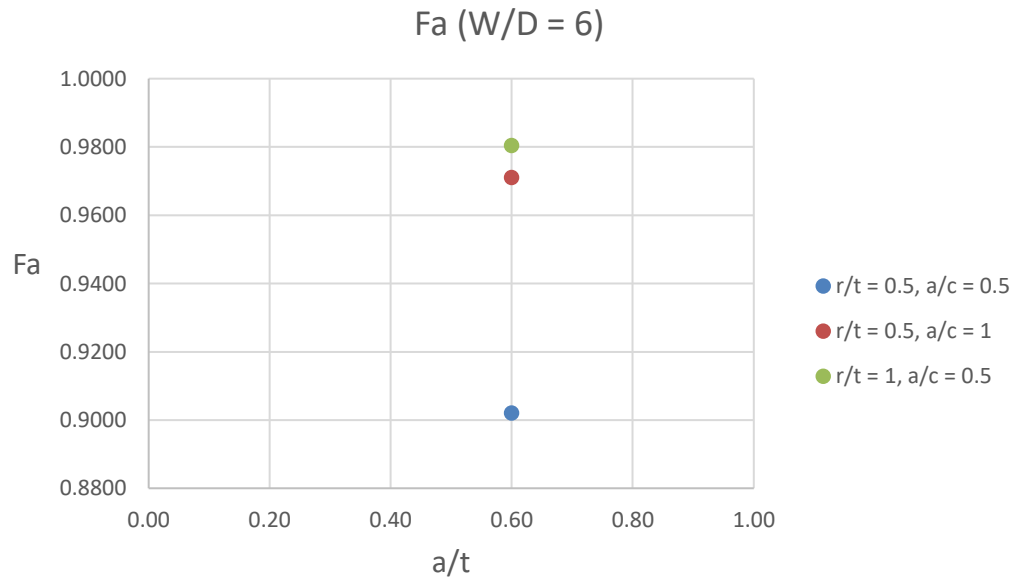




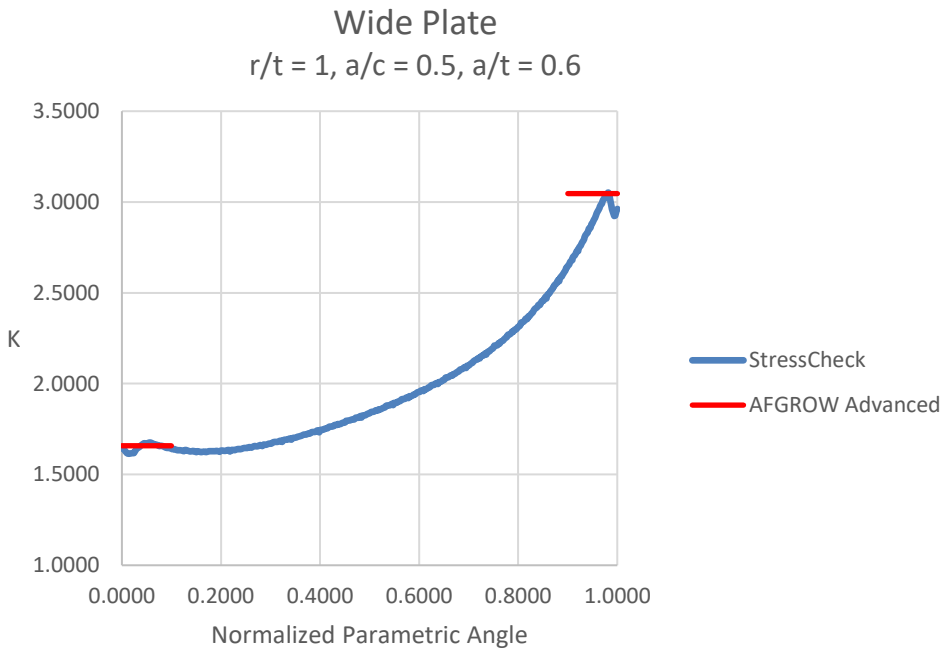
Part-Through Finite Width Correction Examples

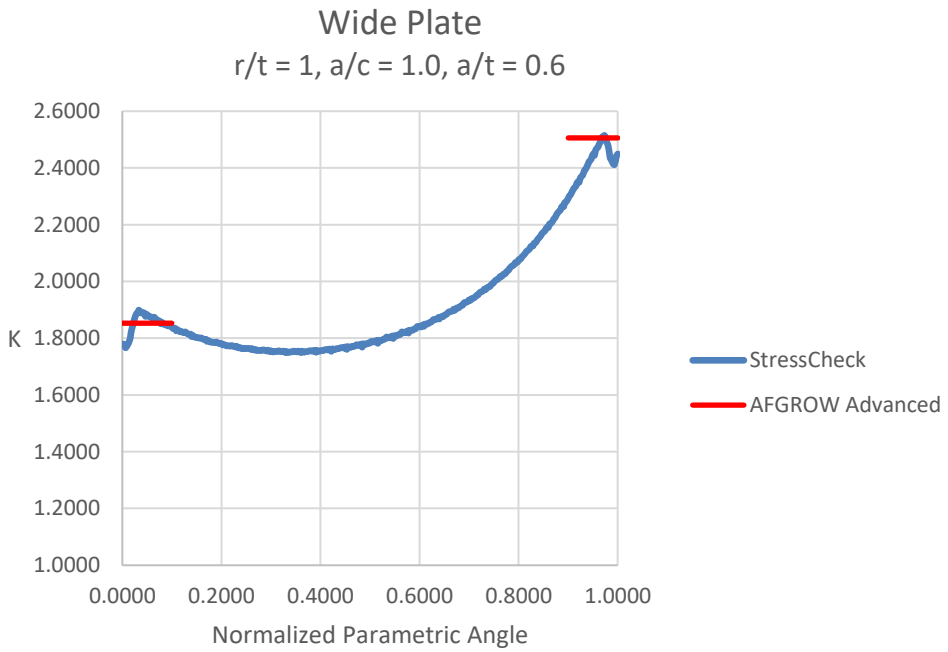
Prost-Domasky (APES) Solutions



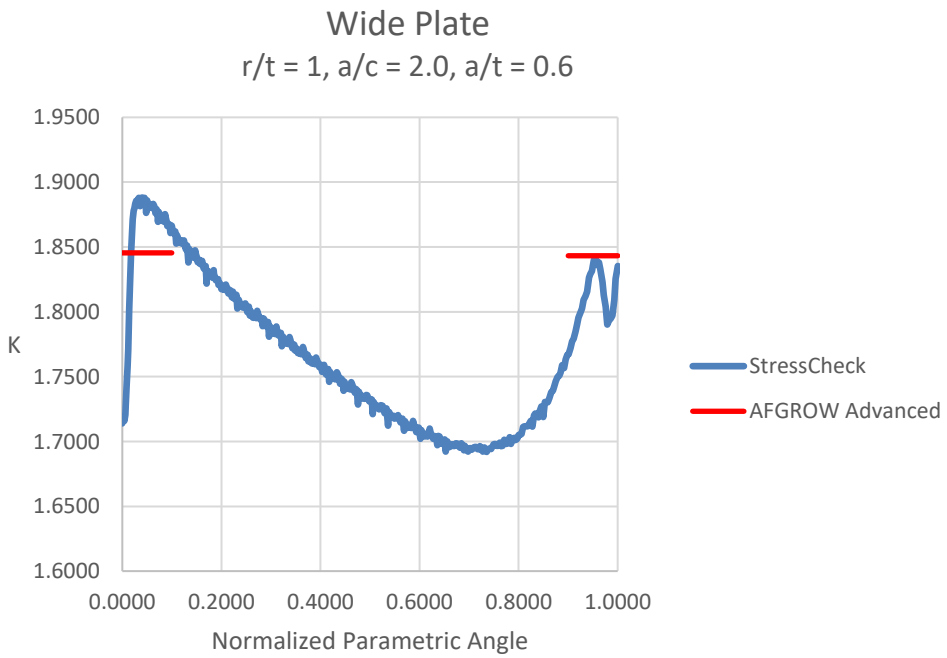


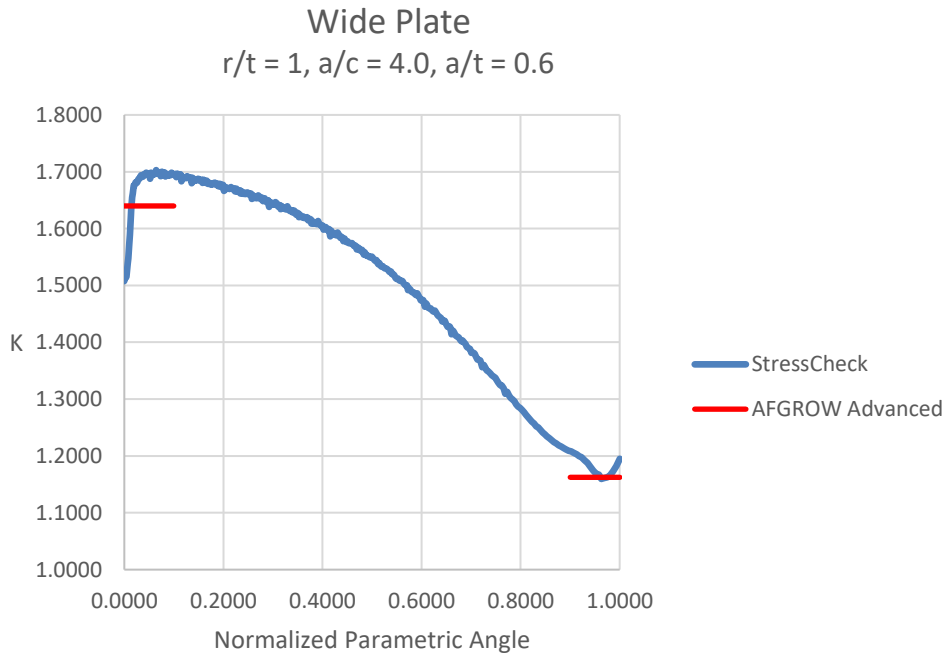
K-Solutions at the Vertices





K-Solutions at the Vertices

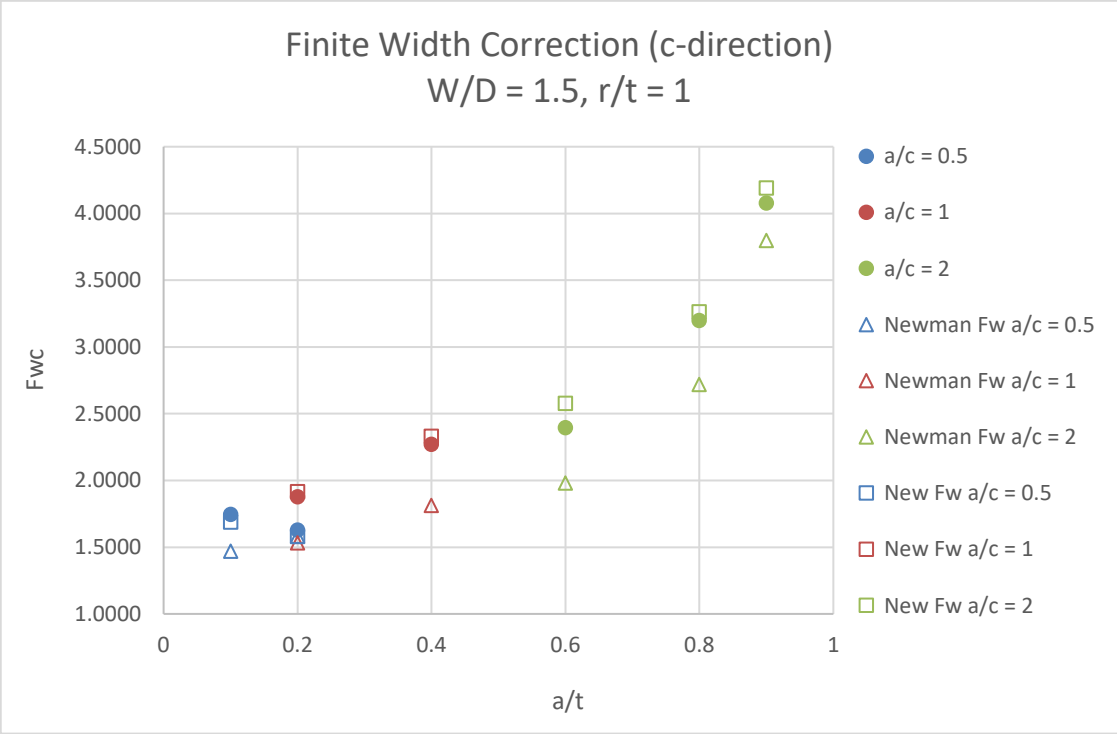


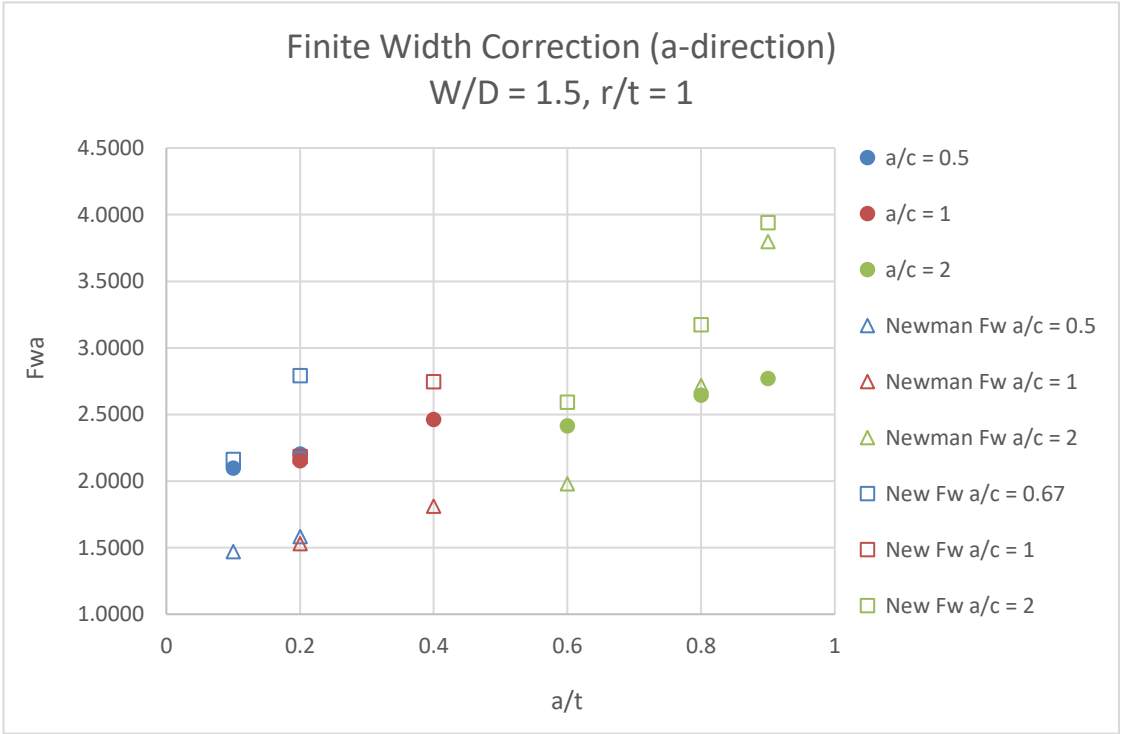


Summary and Conclusions

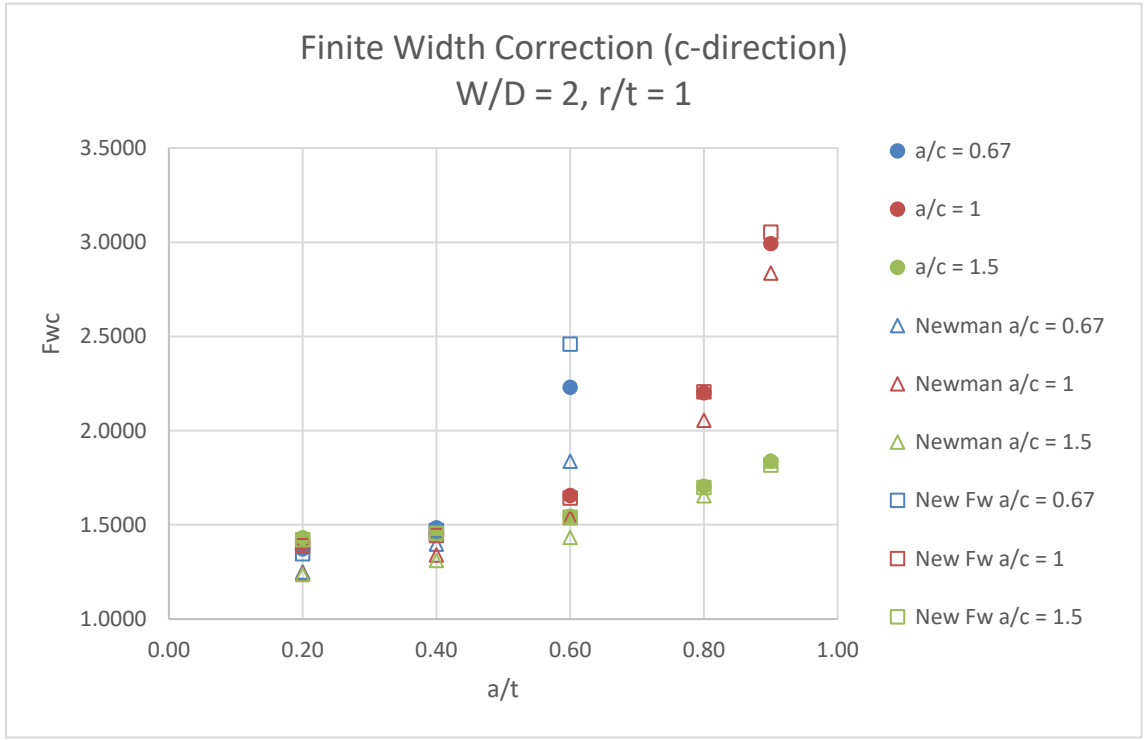
- The current closed-form finite width correction for a single corner crack at an open hole needs to be corrected as soon as possible
- It is now clear that the finite width correction is not the same for all points on the crack front
- It is reasonable to assume that the current correction is also incorrect for double symmetric corner cracks as well as embedded cracks at an open hole
- Work is well underway to develop a new closed-form finite width solution for the single crack case (a and c-directions)
- Scott Prost-Domasky is currently working to resolve the solution noise issue (~2-3%)
- A solution is also needed for multiple point life predictions
- It is important that this issue be resolved before moving forward with any RR efforts for cracks at centered, narrow plates (W/D <= 6) or offset holes (e/D <= 3)

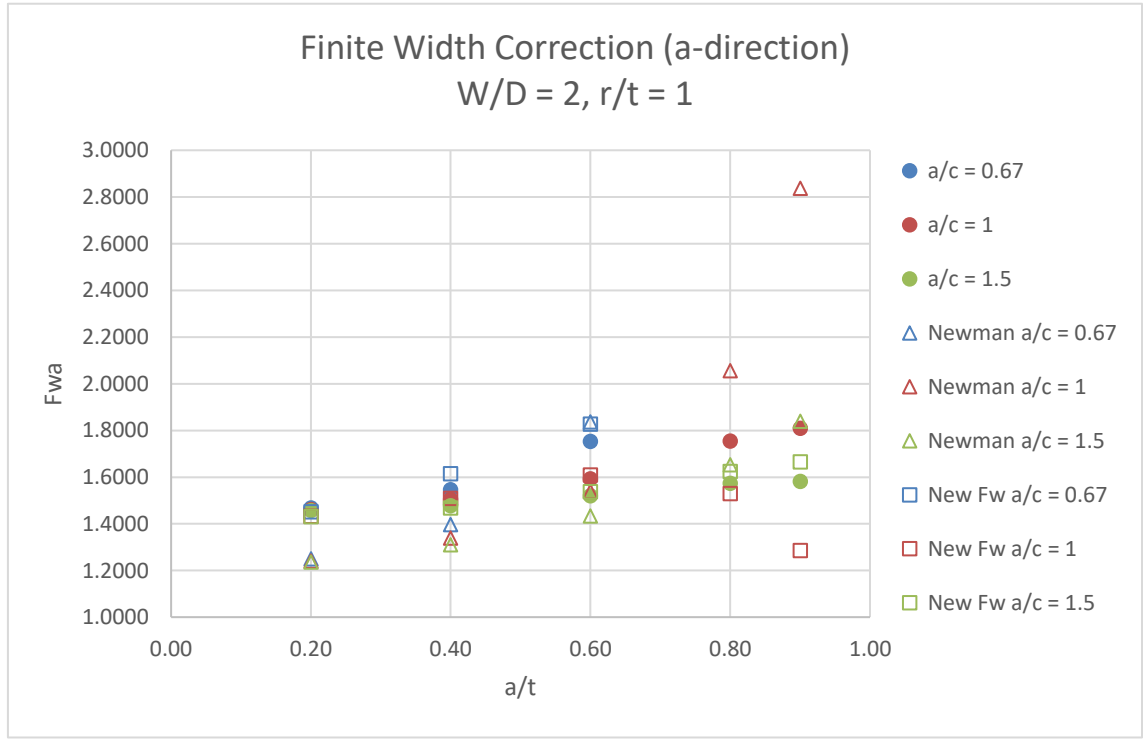
Finite Width Comparison



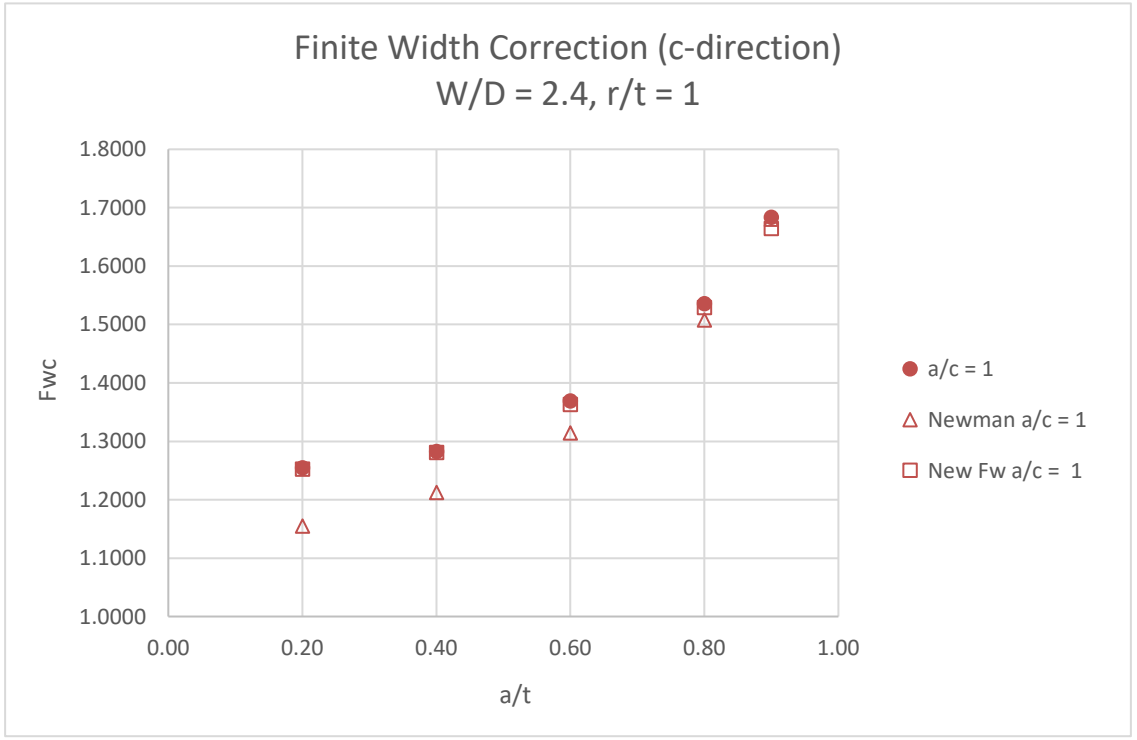


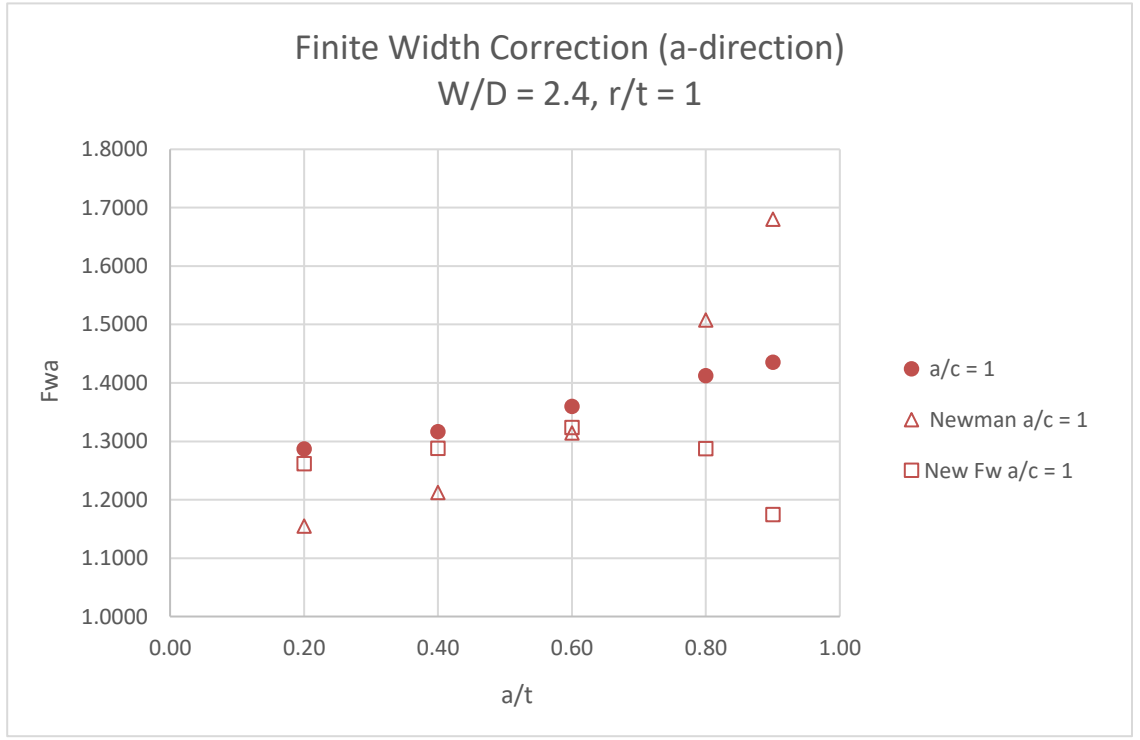
Finite Width Comparison



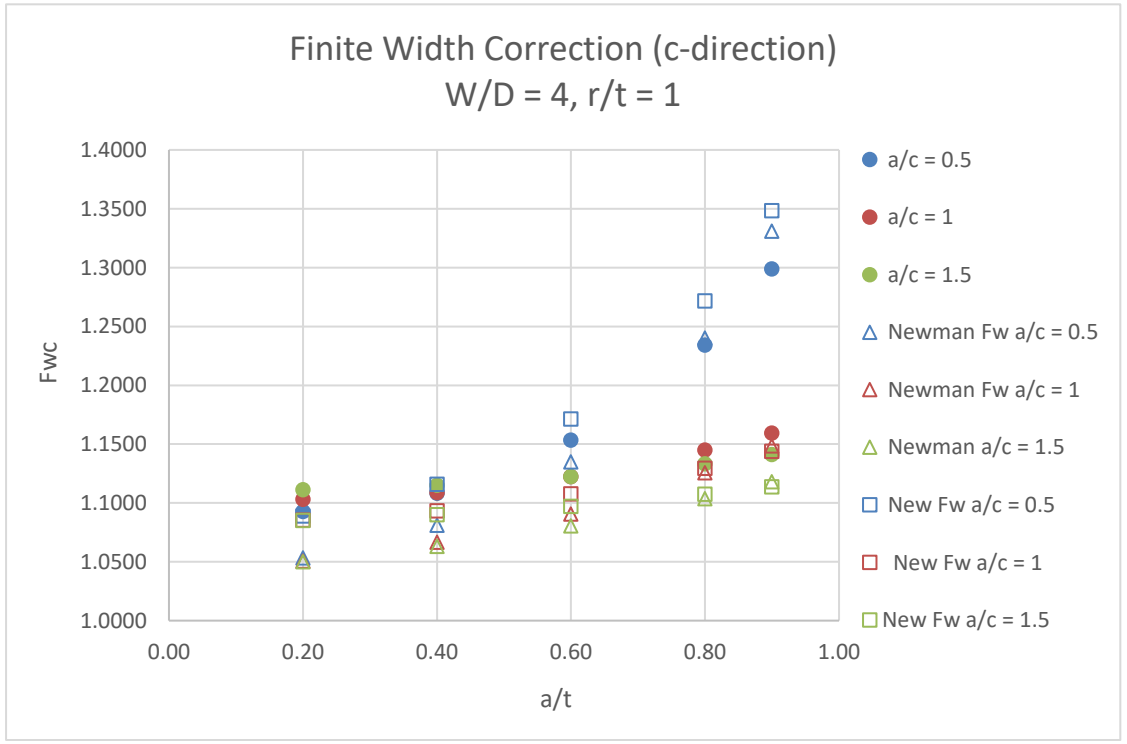


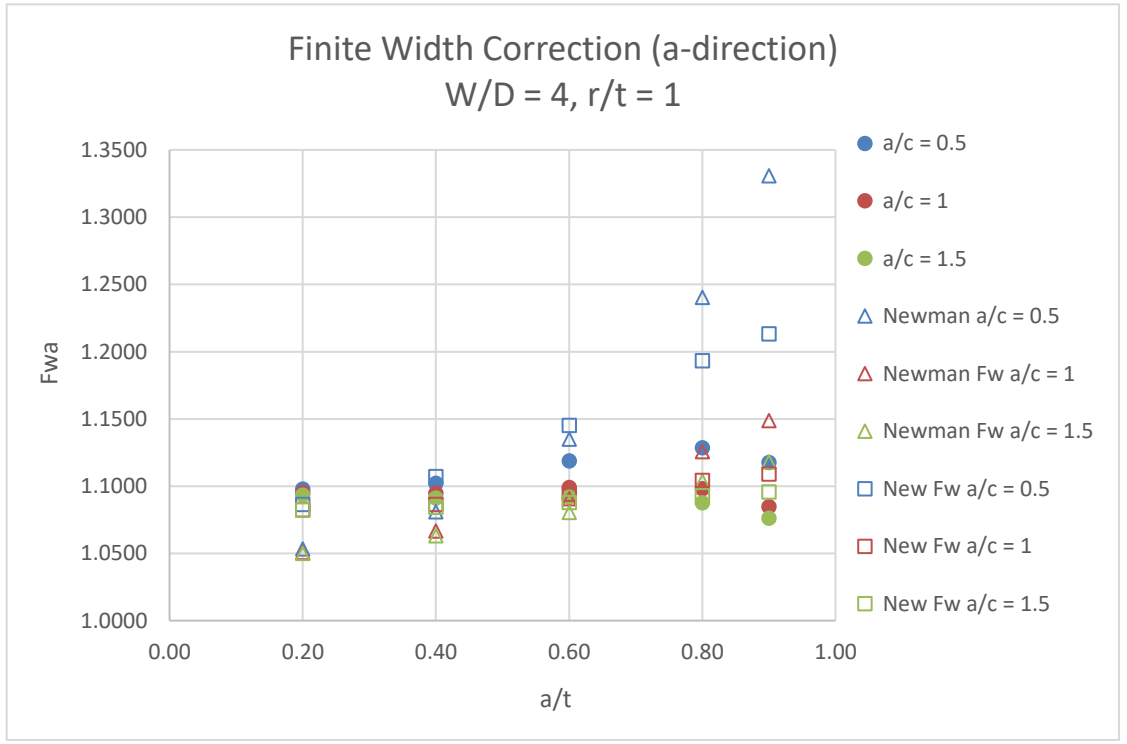
Finite Width Comparison





Finite Width Comparison





Thank You

A special thanks to Dr. Adrian Loghin and Dr. Scott Prost-Domasky for their help running the 3-D FEMs used for this presentation

Recent Changes to the Residual Stress Capability

James Harter, Senior Consultant for LexTech, Inc .

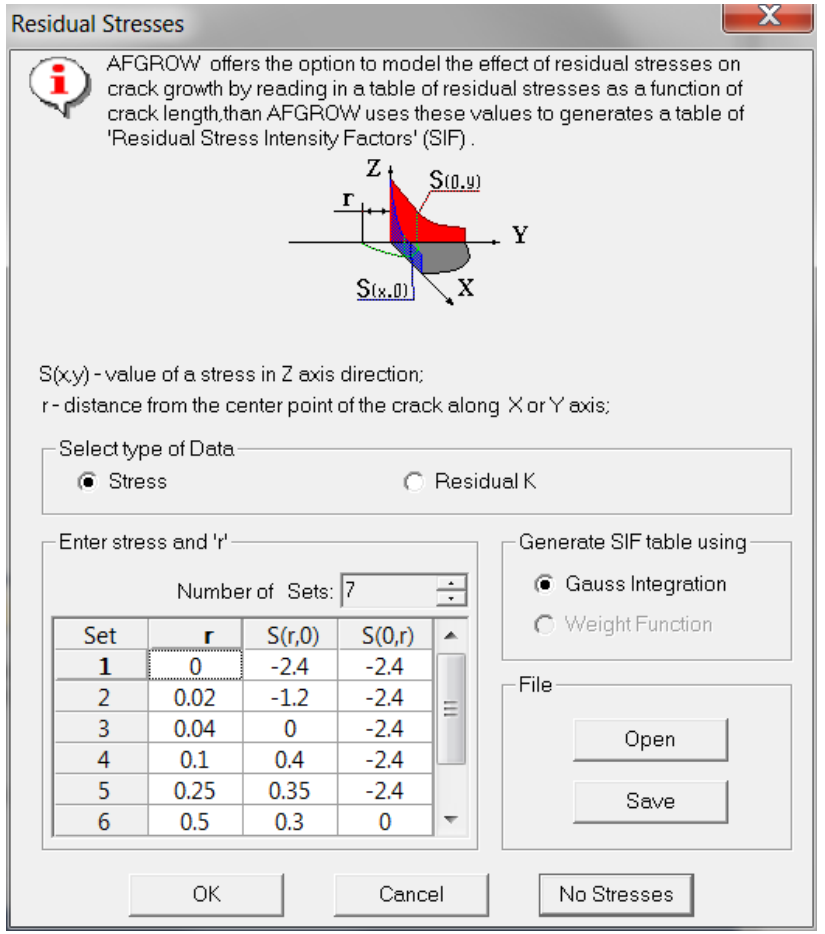
Residual Stress Input

Input Residual Stresses and Calculate Residual Ks

- **1D Weight Function**
- **2D Gaussian Integration**

Similar to the beta correction method, but in this case, the un-flawed residual stress distribution (*not the ratio of two distributions*) is used to calculate K directly.

Note: Since K is not defined for compression, this approach should be considered to be an engineering approximation for compressive residual stresses.



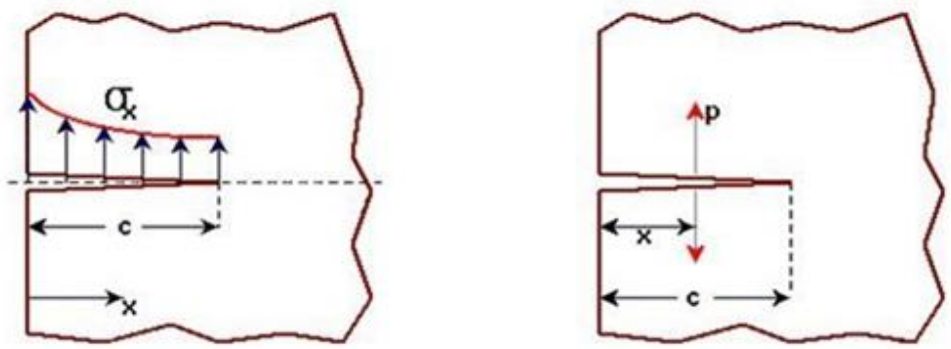
Gaussian Integration Method

2-D Gaussian Integration Method Uses a Point Load Stress Intensity Solution from Tada, Paris, and Irwin

AFGROW uses integration points for each crack growth direction at user-defined radial distances from the crack origin. The residual K value for each crack is determined using the linear interpolation between points.

This method also uses a Newton interpolation algorithm with a 2nd order curve fit using two points beyond each integration point.

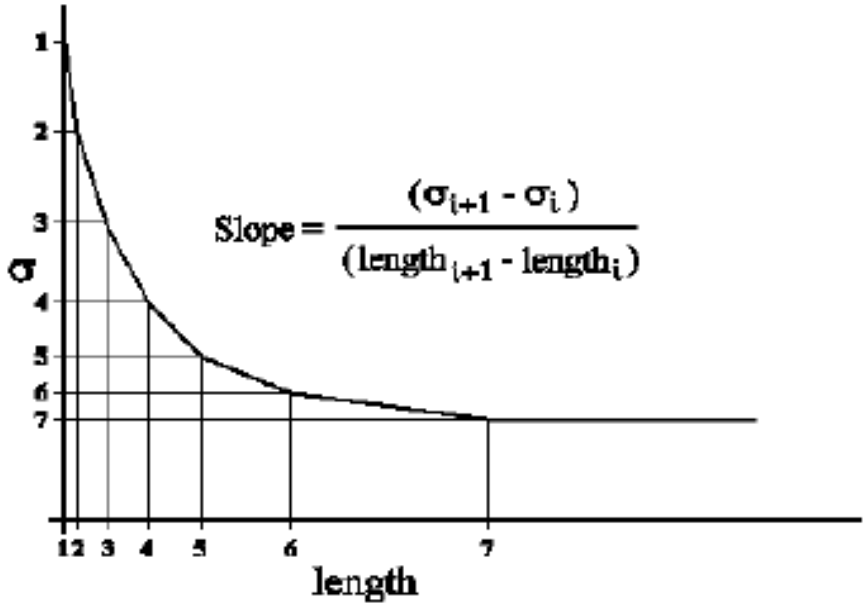
For part through-the-thickness cracks, AFGROW performs two integrations. First, for the initial 2-D case, and then for the 1-D case after transition to a through crack.



$$K_I = \sum_{x=0}^{c} P(x)F(c,x)\,dx$$

Issue

The Gaussian integration method is somewhat sensitive to the change in slope between integration points

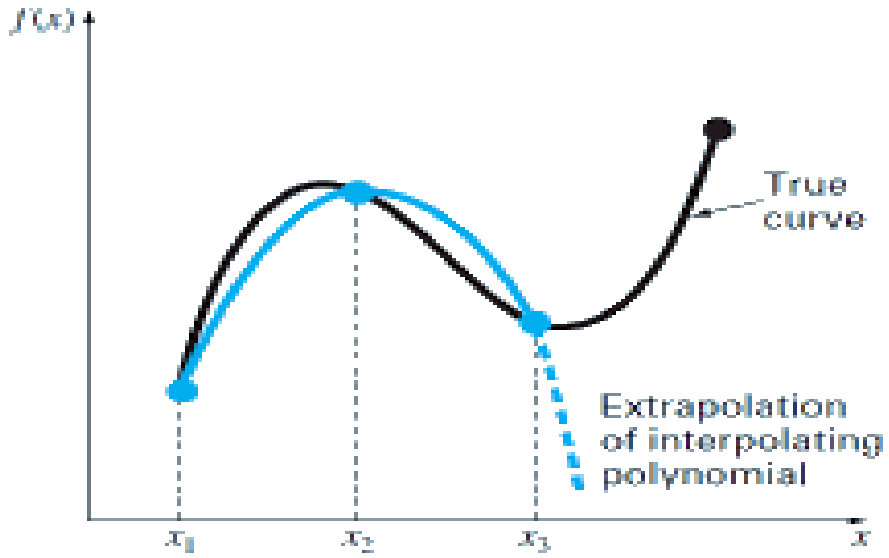


Reasonable results have been obtained with the Gaussian method for:

$$\frac{dSlope}{dr} \leq |600|$$

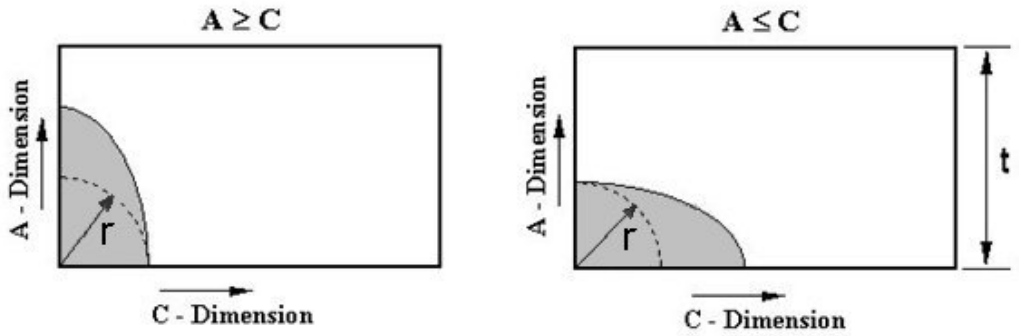
Issue

A Newton polynomial interpolation method is used as part of the Gaussian integration process for each integration point.

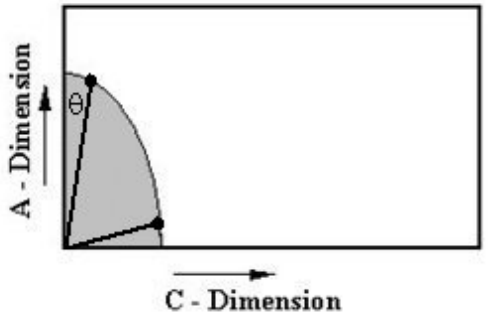


It is highly recommended that two integration points be included beyond the longest expected crack length.

Application Issues for 2-D Cracks



2-D Gaussian integration is based on a radial distance from the crack origin



Appropriate locations on the crack front to apply the residual K values

Gaussian Integration Approach

Changes in Version 5.3

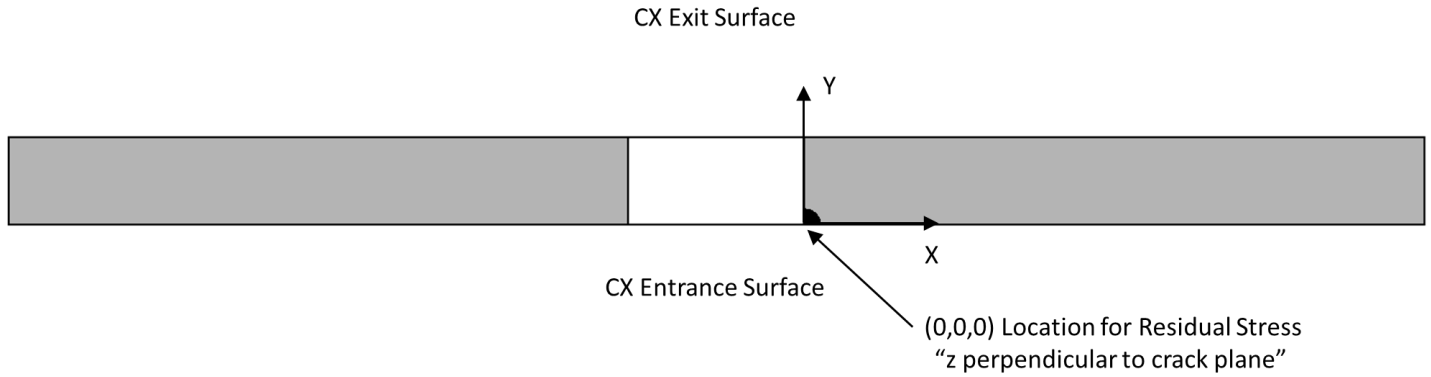
A bug was found and fixed in the Newton interpolation method

For Part Through Cracks:

- **A part-through correction was added to the integration results**
- **Integration is performed twice**
- **Once for the 2-D stress distribution**
- **Second, for the C-direction (distribution in the A-direction is set to 0)**

Residual Stress Example Case

Specimen Geometry



Benchmark Condition #	Material	Specimen Type	Thickness (in)	Width (in)	Hole Diameter (in)	Hole Edge Margin	Loading	Max Stress (ksi)
1	2024-T351	Non-CX Baseline	0.25	4.00	0.50	4.0	CA (R=0.1)	10
2		CX						25
3		Non-CX Baseline				1.2		10
4		CX						25

Material Properties

Property	Value
Material	2024-T351 plate
Modulus (ksi)	10700
Poisson	0.33
Ultimate Strength (ksi)	66
Yield Strength (ksi)	50
Plane Stress Fracture Toughness (ksi-root(inch))	80
Plane Strain Fracture Toughness (ksi-root(inch))	32
Rlo	-0.25
Rhi	0.85

AFGROW Prediction Demonstration

Spectrum Manager Software
Introduction and Demonstration

Matthew Gross, Jimmy Lambert

LexTech, Inc .

AFMAT

Fracture Mechanics Database Demonstration

James Harter, Senior Consultant for LexTech, Inc .

New Tabular Crack Growth Rate Lookup Database

Alexander Litvinov, Matthew Gross

LexTech, Inc .

Additional Parametric Crack Initiation Data

Alexander Litvinov, Matthew Gross, James Harter

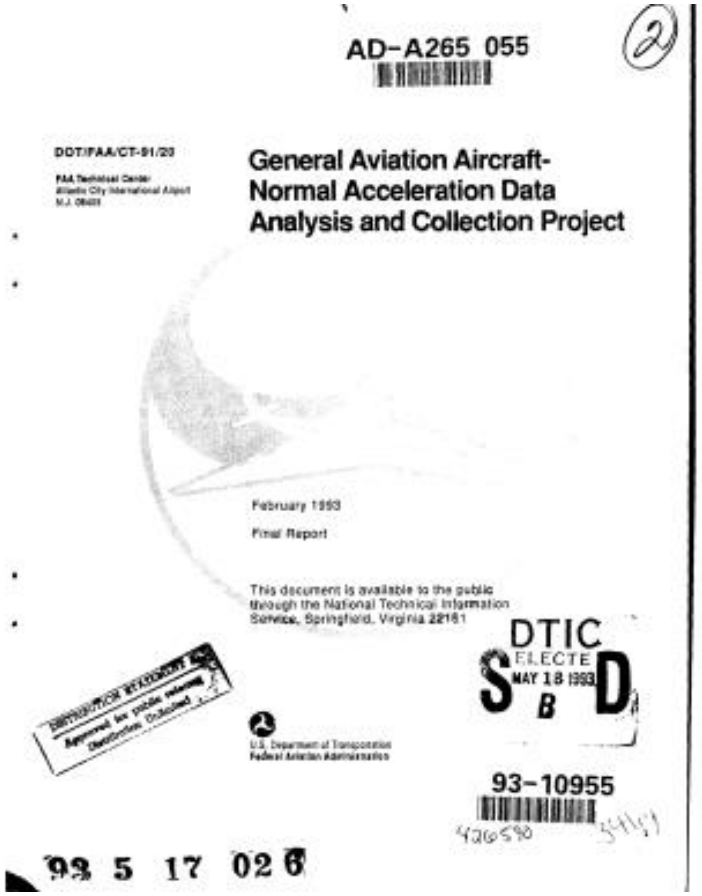
LexTech, Inc .

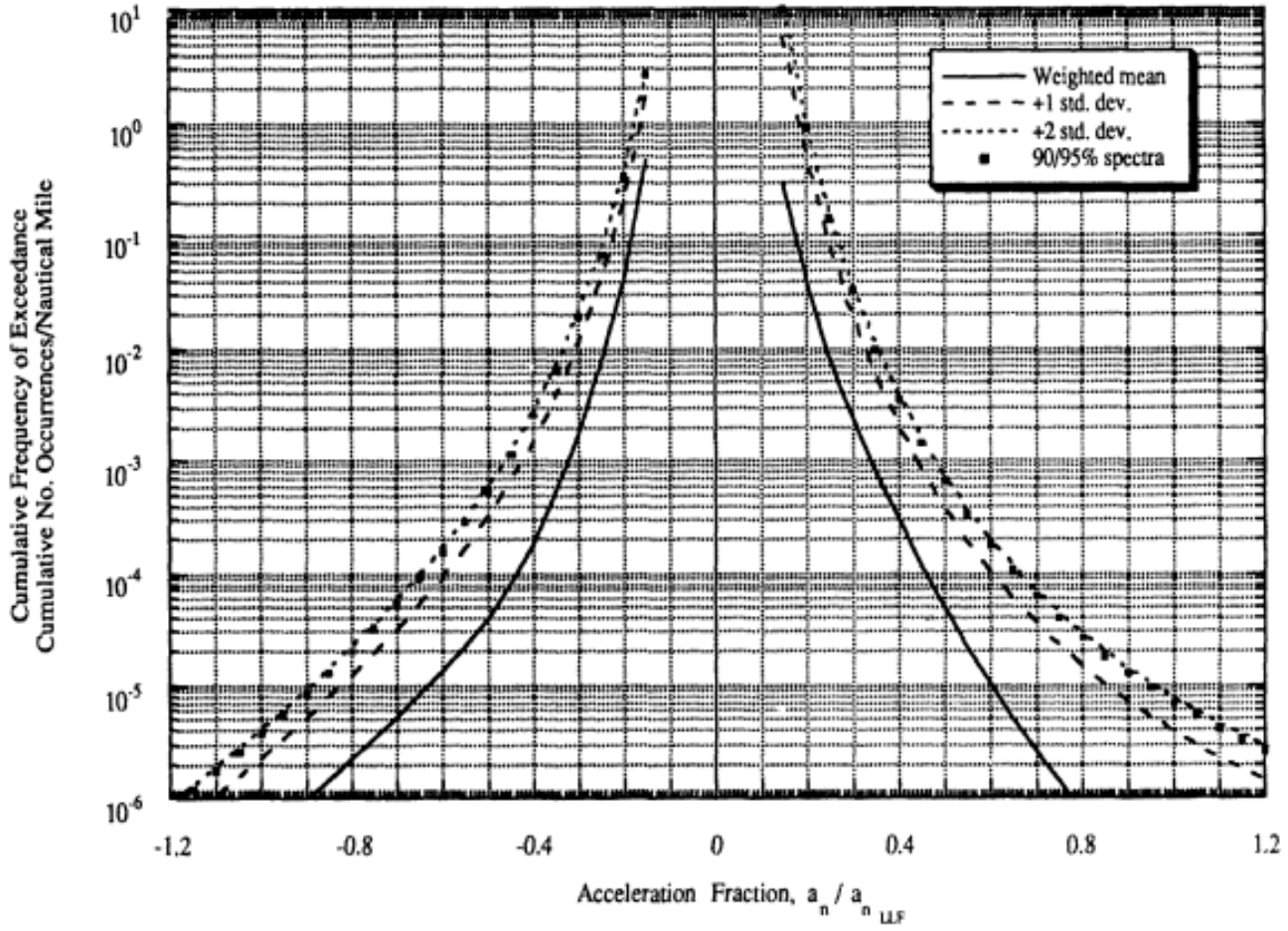
Implementing FAA Gust/Maneuver Exceedance Data in Spectrum Manager

James Harter, Senior Consultant for

LexTech, Inc .

FAA Part 23 Fatigue Program





Is there any interest in a capability to generate input spectra based on FAA gust/maneuver exceedance data?

New API 579 Pipeline Crack Solutions

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